

# **Benchmarking the Integration of WAVEWATCH III Results into HAZUS-MH<sup>®</sup>: Preliminary Results**

*NASA Applied Sciences Program Integrated Product Team for Disaster Management  
John C. Stennis Space Center, Mississippi*

National Aeronautics and  
Space Administration

John C. Stennis Space Center  
SSC, Mississippi 39529-6000

---

December 2005

### Acknowledgments

This report is a joint work of employees of the National Aeronautics and Space Administration and employees of Science Systems and Applications, Inc., under Task Order NNS04AB54T.

Applied Sciences Program Integrated Product Team (IPT) for Disaster Management:

Steve Ambrose, *NASA Applied Sciences Program, HQ – Program Manager*

\* Judith Berglund, *SSAI Applied Sciences Directorate, SSC*

\* Donald Holland, *SSAI Applied Sciences Directorate, SSC*

Frank Lavelle, *Applied Research Associates, Raleigh, NC*

\* Rodney McKellip, *NASA Applied Sciences Directorate, SSC – Deputy Program Manager, Team Leader*

Barbara Schauer, *National Institute of Building Sciences, Washington, DC*

\* Jeff Sciaudone, *Applied Research Associates, Raleigh, NC*

Joseph Spruce, *SSAI Applied Sciences Directorate, SSC*

\* Peter Vickery, *Applied Research Associates, Raleigh, NC*

\* Zhanxian Wang, *Applied Research Associates, Raleigh, NC*

\* Ken Ying, *Applied Research Associates, Raleigh, NC*

\* Members involved in drafting this report

Trade names and trademarks are used in this report for identification only. Their usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

## Table of Contents

Executive Summary .....	v
1.0 Introduction.....	1
1.1 Disaster Management Program Element.....	1
1.2 Systems Engineering Approach and Integrated System Solutions Architecture .....	2
1.3 Relationship to HAZUS-MH DSS .....	2
2.0 Determination of Loss Estimates from Hurricane-induced Coastal Flooding using HAZUS-MH and Associated Models .....	3
2.1 Coastal Flood Parameters.....	3
2.2 Relevant Models .....	4
2.2.1 Hurricane Simulation Model (HURSIM) and Hurricane Wind Field Model (HURWND).....	5
2.2.2 Surge and Wave Models .....	6
2.2.2.1 HURSURGE .....	6
2.2.2.2 WAVEWATCH III.....	6
2.2.2.3 Simulating Waves Nearshore (SWAN) .....	7
2.2.3 HAZUS-MH Loss Estimation Flood Module.....	7
3.0 Methodology for Preliminary Benchmarking Activity .....	8
3.1 Study Region and Test Case .....	10
3.2 Model Inputs .....	13
4.0 Results and Discussion .....	17
5.0 Preliminary Conclusions .....	21
6.0 References.....	23
Appendix A. Additional Figures.....	27
Appendix B. Results from HAZUS-MH flood module for all study areas and case runs .....	35

## Tables

Table 1. Averaged surge-only and surge-plus-wave-setup values used as input to the HAZUS-MH MR1 flood module for the five study areas. ....	17
Table 2. Results generated by the HAZUS-MH flood module for each study area and each test case. ....	20
Table B-1. Selected results from the “Flood Event Summary Report” produced by HAZUS-MH MR1 flood module for all study areas and case runs. ....	35

## Figures

Figure 1. Overall dataflow through the models at the time of the preliminary benchmark analysis. ....	5
Figure 2. Hurricane Ivan’s storm track as it relates to the study region and estimated wind field (3-second gust wind speeds in mph).....	11
Figure 3. Study areas.....	12
Figure 4. Modeled wind speeds (valid for marine exposure), wave, and surge values from Hurricane Ivan. ....	14
Figure 5. Water elevations as a result of surge-only (A) and surge-plus-wave-setup (B). Units are in meters.....	15
Figure 6. Comparison of surge-only (A) and surge-plus-wave-setup (B) for Baldwin Beaches study area.....	16
Figure 7. DEM of Baldwin Beaches study area, resulting inundation extent from inputting water elevation value for surge-only and surge-plus-wave-setup cases into HAZUS-MH MR1 flood module, and comparison of these inundation extents with FEMA inundation limit. Units are in feet. ....	19
Figure A-1. Comparison of surge-only (A) and surge-plus-wave-setup (B) for Escambia study area. ....	27
Figure A-2. DEM of Escambia study area, resulting inundation extent from inputting water elevation value for surge-only and surge-plus-wave-setup cases into HAZUS-MH MR1 flood module, and comparison of these inundation extents with FEMA inundation limit. Units are in feet.....	28
Figure A-3. Comparison of surge-only (A) and surge-plus-wave-setup (B) for West Santa Rosa (northeast side) and North Pensacola (southwest side) study areas.....	29
Figure A-4. DEM of West Santa Rosa study area, resulting inundation extent from inputting water elevation value for surge-only and surge-plus-wave-setup cases into HAZUS-MH MR1 flood module, and comparison of these inundation extents with FEMA inundation limit. Units are in feet. ....	30
Figure A-5. DEM of North Pensacola study area, resulting inundation extent from inputting water elevation value for surge-only and surge-plus-wave-setup cases into HAZUS-MH MR1 flood module, and comparison of these inundation extents with FEMA inundation limit. Units are in feet. ....	31
Figure A-6. Comparison of surge-only (A) and surge-plus-wave-setup (B) for Perdido Bay study area...	32
Figure A-7. DEM of Perdido Bay study area, resulting inundation extent from inputting water elevation value for surge-only and surge-plus-wave-setup cases into HAZUS-MH MR1 flood module, and comparison of these inundation extents with FEMA inundation limit. Units are in feet.....	33



## Figures

Figure 1. Overall dataflow through the models at the time of the preliminary benchmark analysis. ....	5
Figure 2. Hurricane Ivan’s storm track as it relates to the study region and estimated wind field (3-second gust wind speeds in mph).....	11
Figure 3. Study areas.....	12
Figure 4. Modeled wind speeds (valid for marine exposure), wave, and surge values from Hurricane Ivan. ....	14
Figure 5. Water elevations as a result of surge-only (A) and surge-plus-wave-setup (B). Units are in meters.....	15
Figure 6. Comparison of surge-only (A) and surge-plus-wave-setup (B) for Baldwin Beaches study area.....	16
Figure 7. DEM of Baldwin Beaches study area, resulting inundation extent from inputting water elevation value for surge-only and surge-plus-wave-setup cases into HAZUS-MH MR1 flood module, and comparison of these inundation extents with FEMA inundation limit. Units are in feet. ....	19
Figure A-1. Comparison of surge-only (A) and surge-plus-wave-setup (B) for Escambia study area.....	27
Figure A-2. DEM of Escambia study area, resulting inundation extent from inputting water elevation value for surge-only and surge-plus-wave-setup cases into HAZUS-MH MR1 flood module, and comparison of these inundation extents with FEMA inundation limit. Units are in feet.....	28
Figure A-3. Comparison of surge-only (A) and surge-plus-wave-setup (B) for West Santa Rosa (northeast side) and North Pensacola (southwest side) study areas.....	29
Figure A-4. DEM of West Santa Rosa study area, resulting inundation extent from inputting water elevation value for surge-only and surge-plus-wave-setup cases into HAZUS-MH MR1 flood module, and comparison of these inundation extents with FEMA inundation limit. Units are in feet. ....	30
Figure A-5. DEM of North Pensacola study area, resulting inundation extent from inputting water elevation value for surge-only and surge-plus-wave-setup cases into HAZUS-MH MR1 flood module, and comparison of these inundation extents with FEMA inundation limit. Units are in feet. ....	31
Figure A-6. Comparison of surge-only (A) and surge-plus-wave-setup (B) for Perdido Bay study area...	32
Figure A-7. DEM of Perdido Bay study area, resulting inundation extent from inputting water elevation value for surge-only and surge-plus-wave-setup cases into HAZUS-MH MR1 flood module, and comparison of these inundation extents with FEMA inundation limit. Units are in feet.....	33

## Executive Summary

Storm surge is the largest component in coastal flooding when hurricanes make landfall. When storm surge is combined with “wave effects” (such as wave setup, wave crests, and wave runup), the height of the water coming onshore increases, which increases the risk to life and property in hurricane-prone coastal regions of the United States. Deepwater wave models, such as WAVEWATCH III (WW3), can be coupled with nearshore wave models to estimate wave effects, which can be added to surge-only values to yield a more accurate estimate of the height of the water coming onshore during hurricanes. The Hazards U.S. Multi-Hazard (HAZUS-MH<sup>®</sup>) decision support system (DSS) estimates potential losses caused by natural hazards. HAZUS-MH MR1, the version of HAZUS-MH that was publicly available at the time of this study, predicted loss estimates from coastal flooding using only values of surge. In fiscal years (FY) 2004–2005, NASA’s Disaster Management Program funded an activity with the National Institute of Building Sciences (NIBS) and with Applied Research Associates (ARA) to enhance the ability of HAZUS-MH to improve wind and wave assessments through the use of WW3, a NASA-heritage model.

This report describes the results from the preliminary benchmarking activities associated with the use of WW3 results in the HAZUS-MH MR1 flood module. Benchmarking, one of the three phases of the systems engineering approach used by NASA’s Applied Sciences Program, is the process of comparing results before and after the inclusion of a new dataset or algorithm to determine improvements in operation, function, or performance over the earlier method. The benchmarking process is required to support adoption of innovative solutions into operational environments that affect life and property. The methodology in HAZUS-MH MR1 uses water levels estimated using only surge models. By integrating the WW3 deepwater wave model with a nearshore wave model in future versions of HAZUS-MH, wave setup can be added to surge values to yield more realistic and accurate water levels for coastal flooding as storms make landfall. These more accurate flood elevations that include wave setup with surge are expected to improve loss estimates generated by the HAZUS-MH flood module. This preliminary benchmarking study compares loss estimates generated by the HAZUS-MH MR1 flood module before and after the inclusion of WW3 results. It is preliminary because the HAZUS-MH flood module was still under development at the time of the study. In addition, WW3 is not scheduled to be fully integrated with HAZUS-MH and available for public release until 2008.

This benchmarking activity was conducted in the coastal Alabama/Florida Panhandle region in five study areas. Surge-only values were modeled for Hurricane Ivan using the HURSURGE model. Wave setup values were modeled for Hurricane Ivan using the WW3 model (coupled with the Simulating Waves Nearshore or SWAN model) and then added to the surge-only values to obtain surge-plus-wave-setup values. HURSURGE, WW3, and SWAN have all been separately validated by various researchers. These values for surge-only and for surge-plus-wave-setup were then entered into the HAZUS-MH MR1 flood module to obtain loss estimates. In each of the five study areas, adding the wave setup to the surge-only output predicted greater depths of water—from 1 to 3 feet. The increased flood depth estimates translated into greater economic loss estimates (as expected). The increases in total economic loss estimates ranged from \$13 million to \$90 million for the five study areas. Percent differences between total economic loss estimates from surge-only and from surge-plus-wave-setup ranged from 15 to 57 percent for these study areas, thus indicating the change resulting from adding wave setup to surge.

The Federal Emergency Management Agency (FEMA) mapped inundation limits using surveyed high water marks from Hurricane Ivan. The inundation limits were qualitatively compared with the depth grids and flooding extents generated by the HAZUS-MH MR1 flood module when values of surge-only and surge-plus-wave-setup were entered to calculate damage loss estimates. Because the HAZUS-MH flood

module was still being developed at the time of this study, it was not reasonable to expect a close comparison. At the time of this study, the HAZUS-MH MR1 flood module generated the flooding depth grids and extents by using a single user-supplied value or stillwater elevation for the surge-only or surge-plus-wave-setup cases on a digital elevation model to determine which areas were inundated and thus which buildings would have been flooded/damaged. When determining areas of inundation and damage estimates, the HAZUS-MH MR1 flood module did not yet take into account the retarding effect of the ground surface (“land friction”), buildings, or other obstacles (“form friction”) on the flow of water as it moved inland, or the effect of wind pushing waves further inland when storms made landfall. These conditions (i.e., wind effects and friction caused by land and obstacles) would obviously have affected the flooding extent during the event (captured in the FEMA inundation limit validation data), thus providing an explanation for the overestimation of the modeled flooding extent. In addition, the use of only one value for flood elevation for an entire study area in the HAZUS-MH MR1 flood module instead of a grid of variable flood elevations also obviously would have affected the results significantly.

In summary, it must be stressed that this benchmarking study is preliminary because when the study was performed, the storm surge and wave models (such as WW3 and SWAN) were not fully coupled and integrated into HAZUS-MH, and the HAZUS-MH flood module was still under development. The approach taken in this study is consistent with the approach a user of HAZUS-MH MR1 would have to take to perform a scenario coastal study. Still, the results from this preliminary study are very promising. This was an excellent opportunity to gauge preliminary results with real-world events—to demonstrate the potential improvements in loss estimates by incorporating wave setup with storm surge through the use of WW3 and to demonstrate the feasibility of the HAZUS-MH flood module to provide reliable information to coastal resource managers and emergency planners.

Several physical parameters are still being integrated into HAZUS-MH, including the effect of wind on the waves, land and form friction (obstacles to water flow), and more accurate terrain and bathymetry. The major integration step includes fully coupling HURSURGE, WW3, and SWAN to produce estimates of stillwater elevation rise and wave heights that better model the physical process. As each of these parameters and surge/wave models are integrated into HAZUS-MH, an improved and more robust model product would be expected, yielding more accurate results. When development is complete, the HAZUS wind and coastal flood models will be seamlessly integrated to estimate wind and flooding losses from hurricanes. When this enhanced version of HAZUS-MH is released to the public in 2008, a more comprehensive benchmark analysis will need to be performed. Model results before and after the full integration of WW3 can then be compared with real-world validation data to determine the magnitude/extent of the improvements to loss estimates. These improved loss estimates can then be more fully utilized by planners and responders to mitigate and prevent loss of life and property as a result of hurricanes.

## Executive Summary

Storm surge is the largest component in coastal flooding when hurricanes make landfall. When storm surge is combined with “wave effects” (such as wave setup, wave crests, and wave runup), the height of the water coming onshore increases, which increases the risk to life and property in hurricane-prone coastal regions of the United States. Deepwater wave models, such as WAVEWATCH III (WW3), can be coupled with nearshore wave models to estimate wave effects, which can be added to surge-only values to yield a more accurate estimate of the height of the water coming onshore during hurricanes. The Hazards U.S. Multi-Hazard (HAZUS-MH<sup>®</sup>) decision support system (DSS) estimates potential losses caused by natural hazards. HAZUS-MH MR1, the version of HAZUS-MH that was publicly available at the time of this study, predicted loss estimates from coastal flooding using only values of surge. In fiscal years (FY) 2004–2005, NASA’s Disaster Management Program funded an activity with the National Institute of Building Sciences (NIBS) and with Applied Research Associates (ARA) to enhance the ability of HAZUS-MH to improve wind and wave assessments through the use of WW3, a NASA-heritage model.

This report describes the results from the preliminary benchmarking activities associated with the use of WW3 results in the HAZUS-MH MR1 flood module. Benchmarking, one of the three phases of the systems engineering approach used by NASA’s Applied Sciences Program, is the process of comparing results before and after the inclusion of a new dataset or algorithm to determine improvements in operation, function, or performance over the earlier method. The benchmarking process is required to support adoption of innovative solutions into operational environments that affect life and property. The methodology in HAZUS-MH MR1 uses water levels estimated using only surge models. By integrating the WW3 deepwater wave model with a nearshore wave model in future versions of HAZUS-MH, wave setup can be added to surge values to yield more realistic and accurate water levels for coastal flooding as storms make landfall. These more accurate flood elevations that include wave setup with surge are expected to improve loss estimates generated by the HAZUS-MH flood module. This preliminary benchmarking study compares loss estimates generated by the HAZUS-MH MR1 flood module before and after the inclusion of WW3 results. It is preliminary because the HAZUS-MH flood module was still under development at the time of the study. In addition, WW3 is not scheduled to be fully integrated with HAZUS-MH and available for public release until 2008.

This benchmarking activity was conducted in the coastal Alabama/Florida Panhandle region in five study areas. Surge-only values were modeled for Hurricane Ivan using the HURSURGE model. Wave setup values were modeled for Hurricane Ivan using the WW3 model (coupled with the Simulating Waves Nearshore or SWAN model) and then added to the surge-only values to obtain surge-plus-wave-setup values. HURSURGE, WW3, and SWAN have all been separately validated by various researchers. These values for surge-only and for surge-plus-wave-setup were then entered into the HAZUS-MH MR1 flood module to obtain loss estimates. In each of the five study areas, adding the wave setup to the surge-only output predicted greater depths of water—from 1 to 3 feet. The increased flood depth estimates translated into greater economic loss estimates (as expected). The increases in total economic loss estimates ranged from \$13 million to \$90 million for the five study areas. Percent differences between total economic loss estimates from surge-only and from surge-plus-wave-setup ranged from 15 to 57 percent for these study areas, thus indicating the change resulting from adding wave setup to surge.

The Federal Emergency Management Agency (FEMA) mapped inundation limits using surveyed high water marks from Hurricane Ivan. The inundation limits were qualitatively compared with the depth grids and flooding extents generated by the HAZUS-MH MR1 flood module when values of surge-only and surge-plus-wave-setup were entered to calculate damage loss estimates. Because the HAZUS-MH flood

module was still being developed at the time of this study, it was not reasonable to expect a close comparison. At the time of this study, the HAZUS-MH MR1 flood module generated the flooding depth grids and extents by using a single user-supplied value or stillwater elevation for the surge-only or surge-plus-wave-setup cases on a digital elevation model to determine which areas were inundated and thus which buildings would have been flooded/damaged. When determining areas of inundation and damage estimates, the HAZUS-MH MR1 flood module did not yet take into account the retarding effect of the ground surface (“land friction”), buildings, or other obstacles (“form friction”) on the flow of water as it moved inland, or the effect of wind pushing waves further inland when storms made landfall. These conditions (i.e., wind effects and friction caused by land and obstacles) would obviously have affected the flooding extent during the event (captured in the FEMA inundation limit validation data), thus providing an explanation for the overestimation of the modeled flooding extent. In addition, the use of only one value for flood elevation for an entire study area in the HAZUS-MH MR1 flood module instead of a grid of variable flood elevations also obviously would have affected the results significantly.

In summary, it must be stressed that this benchmarking study is preliminary because when the study was performed, the storm surge and wave models (such as WW3 and SWAN) were not fully coupled and integrated into HAZUS-MH, and the HAZUS-MH flood module was still under development. The approach taken in this study is consistent with the approach a user of HAZUS-MH MR1 would have to take to perform a scenario coastal study. Still, the results from this preliminary study are very promising. This was an excellent opportunity to gauge preliminary results with real-world events—to demonstrate the potential improvements in loss estimates by incorporating wave setup with storm surge through the use of WW3 and to demonstrate the feasibility of the HAZUS-MH flood module to provide reliable information to coastal resource managers and emergency planners.

Several physical parameters are still being integrated into HAZUS-MH, including the effect of wind on the waves, land and form friction (obstacles to water flow), and more accurate terrain and bathymetry. The major integration step includes fully coupling HURSURGE, WW3, and SWAN to produce estimates of stillwater elevation rise and wave heights that better model the physical process. As each of these parameters and surge/wave models are integrated into HAZUS-MH, an improved and more robust model product would be expected, yielding more accurate results. When development is complete, the HAZUS wind and coastal flood models will be seamlessly integrated to estimate wind and flooding losses from hurricanes. When this enhanced version of HAZUS-MH is released to the public in 2008, a more comprehensive benchmark analysis will need to be performed. Model results before and after the full integration of WW3 can then be compared with real-world validation data to determine the magnitude/extent of the improvements to loss estimates. These improved loss estimates can then be more fully utilized by planners and responders to mitigate and prevent loss of life and property as a result of hurricanes.

## 1.0 Introduction

In fiscal years (FY) 2004–2005, NASA’s Disaster Management Program funded an activity to enhance the ability of the Hazards U.S. Multi-Hazard (HAZUS-MH<sup>®</sup>) decision support system (DSS) to estimate flood losses through the use of WAVEWATCH III (WW3), a NASA-heritage model. HAZUS-MH MR1, the version of HAZUS that was publicly available at the time of this study, used only values of surge that did not include wave effects. Deepwater wave models, such as WW3, can be coupled with nearshore wave models to estimate wave effects, which can be added to surge-only values to produce a more accurate estimate of the height of the water coming onshore during hurricanes. These more accurate flood elevations that include wave setup with surge are expected to improve loss estimates generated by the HAZUS-MH flood module. The significance and importance of having better estimates of these water levels and a better understanding of the potential impact in terms of loss to the coastal communities was made even more apparent by the utterly devastating effects of storm surge combined with wave effects on life and property during Hurricane Katrina on August 29, 2005. By using water levels that include both surge and wave effects in HAZUS-MH, officials at all levels of government can better predict estimated losses as a result of hurricane-force winds and related coastal flooding, which is critical to the protection of life and property. More-informed decisions can then be made about shelter requirements and allocation of disaster response resources just before or following the event and about loss mitigation when planning for development in coastal communities.

One of the steps in determining the usefulness and improved accuracy in the results gained by incorporating data from the WW3 model into HAZUS-MH is benchmarking. Benchmarking is the process of comparing results before and after the inclusion of a new dataset or algorithm to determine improvements in operation, function, or performance over the earlier method. The following sections briefly describe the Disaster Management Program, the integrated systems solutions architecture, and their relationship to HAZUS-MH. The remainder of the report describes the preliminary benchmarking analysis associated with the use of WW3 results in the HAZUS-MH MR1 flood module. Full integration of the WW3 model into HAZUS-MH is not scheduled to be completed and released to the public until 2008, and the HAZUS-MH flood module is still under development. Therefore, results presented in this report will be preliminary.

### 1.1 Disaster Management Program Element

Disaster Management is one of twelve program elements in the NASA Science Mission Directorate’s Applied Sciences Program. The goal of the Disaster Management Program is as follows:

*Enable partners’ beneficial use of NASA Science research results, observations, models, and technologies to enhance decision support capabilities serving their disaster management, disaster warning, risk reduction, and policy responsibilities ([NASA, 2005a](#), p. 4).*

The Disaster Management Program will achieve its goals through the following activities:

- Develop and nurture partnerships and networks with appropriate disaster management organizations
- Identify and assess partners’ disaster management responsibilities, plans, and decision support tools, and evaluate the capacity of NASA science results to support these partners

- Validate and verify application of science results with partners, including development of products and prototypes to meet partners' requirements
- With partners, document, verify, and validate the value of Science results in decision support tools and support the tools' adoption into operational use
- Communicate results and partners' achievements to appropriate disaster management communities and stakeholders
- Advance NASA exploration objectives in the new Science Mission Directorate where opportunities and Earth-Sun system science and applications enable the success of planetary and space exploration ([NASA, 2005a](#)).

## 1.2 Systems Engineering Approach and Integrated System Solutions Architecture

The Applied Sciences Program employs both a systems engineering approach and an integrated system solutions architecture in the execution of its projects. For additional information, refer to the *NASA Earth Science Applications Plan* ([NASA, 2004](#)) and *The Crosscutting Solutions Program* ([NASA, 2005b](#)) for further information.

## 1.3 Relationship to HAZUS-MH DSS

HAZUS-MH is a Geographic Information System (GIS) based decision support tool developed by the U.S. Federal Government for estimation of potential losses caused by natural hazards and other disasters. The Department of Homeland Security's Federal Emergency Management Agency (DHS/FEMA) oversees HAZUS-MH activities at large, whereas the National Institute of Building Sciences (NIBS) manages this tool's development and implementation for use by the Federal, State, and municipal emergency management communities. FEMA initially released HAZUS in 1999 as HAZUS-99 SR2, primarily as a tool for earthquake disaster risk assessment. HAZUS was expanded in recent years to include hurricanes (wind) as well as riverine and coastal inundation (flood) risk assessments ([NASA, 2005a](#)), and was called HAZUS Multi-Hazard (HAZUS-MH Version 1.0). HAZUS-MH MR1 (HAZUS-MH Version 1.1), released in January 2005, is the version that was available at the time of this preliminary benchmarking study.

Each HAZUS-MH module (earthquake, wind, and flood) allows the user to map, assess, and display geospatial data pertaining to a specific natural hazard to assess and mitigate hazard risk. HAZUS-MH also enables estimation of physical damage to buildings, critical facilities, and other infrastructure. In addition, each hazard-specific module provides estimates of economic loss (e.g., lost jobs, business interruption, repair costs, construction costs) and social impacts (e.g., identifying requirements for shelters and medical aid) based on a variety of census tract information ([NASA, 2005a](#)).

In FY 2003, NASA's Disaster Management Program completed an evaluation report on HAZUS-MH titled *Decision Support Tools Evaluation Report for HAZUS-MH Hurricane Model, Version 1.0* ([NASA, 2003](#)). The evaluation report identified potential improvements that could be gained by the use of NASA data, models, and research in HAZUS-MH, specifically for wind-related risk assessments. It mentions the need for improved flood loss estimates and risk assessments that consider the combined effects of storm surge, waves, and high tides. In response to these needs, the Disaster Management Program's priority activities in FY 2004–2005 focused on extending the ability of the HAZUS-MH DSS.

NASA's objective is to benefit the HAZUS-MH application through the infusion of NASA science research results. Improving the flood loss estimates generated by HAZUS-MH through the integration of WAVEWATCH III, a NASA-heritage model, meets this objective ([NASA, 2005a](#)). Project partner Applied Research Associates (ARA) is integrating WW3 into HAZUS-MH under direction from NIBS and with funding from NASA. The use of deepwater and nearshore wave model results with HAZUS-MH is expected to significantly improve its ability to assess and accurately quantify risk and the resulting damage produced by the combined action of tide and hurricane-induced wind, surge, waves, and dune erosion ([NIBS, 2003](#)). Integrating WW3 into HAZUS-MH is also expected to provide an improved framework for evaluating the cost-effectiveness of hurricane preparation programs for coastal communities.

In FY 2005, one of the Disaster Management Program's priorities that related to HAZUS-MH focused on benchmarking the enhanced capability gained by incorporating WW3 model results into the HAZUS-MH flood module ([NASA, 2005a](#)). *The purpose of this report is to describe the results from the preliminary benchmarking activities associated with the use of WW3 results in the HAZUS-MH MRI flood module.* This benchmarking study is a preliminary analysis because the HAZUS-MH flood module is currently under development. In addition, WAVEWATCH III is not scheduled to be fully integrated with HAZUS-MH and available for public release until 2008. Before discussing the results of the preliminary benchmarking analysis, descriptions will be provided for WW3 and for the other HAZUS-MH model components applicable to this study.

## 2.0 Determination of Loss Estimates from Hurricane-induced Coastal Flooding using HAZUS-MH and Associated Models

### 2.1 Coastal Flood Parameters

*Storm surge* is the largest component of coastal flooding from hurricanes. Storm surge occurs when the dome of water created by the rise in sea level due to the combined effect of circulating winds and the large drop in air pressure near the storm reaches the shallow seafloor of the coastline. The dome of water is forced to rise dramatically above normal water levels on the open coast as the storm moves onshore. The elevation the water reaches, when considered separately from such wave effects as *wave setup*, *wave crest elevation*, and *wave runup* (defined in [NOAA CSC, 2005](#); [ARA, 2005a](#); [State of North Carolina, 2004](#)) is referred to as the *stillwater elevation*.

- Stillwater elevation: projected elevation that flood waters would assume in the absence of wave effects (such as setup, crest, runup) resulting from wind or seismic effects.
- Wave setup: increase in the stillwater elevation caused by waves repeatedly breaking near the shoreline during coastal storms (onshore mass transport by incoming waves).
- Wave crest elevation: additional height above the combined stillwater elevation plus wave setup height due to waves riding on storm surge and setup as the coastal storm moves onshore.
- Wave runup: additional height beyond the stillwater elevation that is reached by waves as wave water is forced up a slope or structure as it rushes inland.
- Wave height: vertical distance between wave crest and wave trough.

Stillwater elevations for the 10% (10-year), 2% (50-year), 1% (100-year), and 0.2% (500-year) annual chance storms are generated by performing *coastal flood studies* that analyze the effects of a direct or near-direct hit on a coastal community by these different intensity storms ([State of North Carolina, 2004](#)).



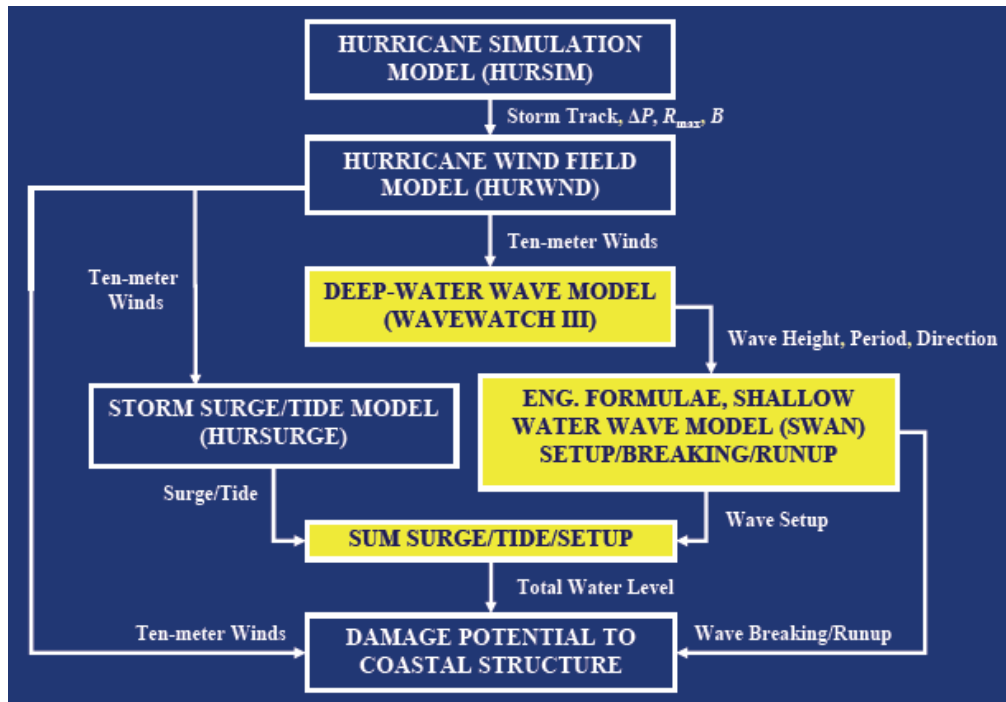
Wave effects, such as wave setup, wave crests, and wave runup, will increase the potential for flood damage in coastal areas. The combined action of storm surge and wave setup can become more severe if their maximum effect should coincide with high astronomical tide. Astronomical tide is caused by gravitational forces between the Earth and other astronomical bodies, such as the Moon and the Sun ([NIBS, 2003](#)). The combination of the 1% annual chance stillwater and wave effect (wave crest, setup, and runup) water elevation above the vertical datum is the *Base Flood Elevation (BFE)* that is shown on Flood Insurance Rate Maps ([State of North Carolina, 2004](#)).

In addition to determining flood elevations, coastal flood studies determine the extent of the *Special Flood Hazard Areas (SFHAs)* where a 1% or greater annual chance of flooding exists. SFHAs are identified as either AE or VE risk zones. The *VE Zone*, or the area designated as the “coastal high hazard area” during coastal flood studies, extends from offshore to the inland limit of a primary frontal dune along an open coast and along any other area inland from the shoreline where wave heights are greater than three feet during the 1% (100-year) annual chance storm. The “V” stands for “velocity wave action,” which indicates that waves in these areas will be powerful enough to break the wall panel of a residential structure away from the floor to which it had been nailed. *AE Zones* are coastal flood areas where wave action does not occur or where wave heights will be less than three feet during a 1% (100-year) annual chance storm. More stringent regulatory requirements exist in VE Zones than in AE Zones. For example, in VE Zones, the bottom of the lowest horizontal structural members supporting the lowest floor of a residential or commercial building must be elevated to or above the BFE. The foundation and attached structure must be designed to resist the combined forces imposed by winds and water during the 1% (100-year) annual chance storm ([State of North Carolina, 2004](#); [NOAA CSC, 2005](#)). Coastal structures are susceptible to flood damage when the water level rises above the stillwater level for which the structure had been designed.

Estimating coastal wind and flood damage is difficult because the wind, surge, tide, and waves are inherently coupled, such that the solutions of tide, surge, and waves cannot simply be added together, nor can the predictions of water-induced damage and wind-induced damage ([NIBS, 2003](#)). The incorporation of WW3 and wave setup is expected to improve flood damage risk assessments from HAZUS-MH.

## 2.2 Relevant Models

A flowchart of the overall dataflow through HAZUS-MH and the approach to calculating storm surge, wave setup, and wave energy flux at coastal locations is depicted in [Figure 1](#) below. The following sections contain a brief description of the models and their roles in the processing dataflow.

Source: [Lavelle, 2005](#)

**Figure 1.** Overall dataflow through the models at the time of the preliminary benchmark analysis.

### 2.2.1 Hurricane Simulation Model (HURSIM) and Hurricane Wind Field Model (HURWND)

The **HURricane SIMulation (HURSIM) model** used in HAZUS-MH was developed by Applied Research Associates with funding from the National Science Foundation ([Twisdale and Vickery, 1992](#)). The model version used in this study is described in detail by [Vickery et al. \(2000a, 2000b\)](#). HURSIM *simulates the tracks of tropical storms and hurricanes* from their initiation over the ocean to their final dissipation, either over land or over the ocean. The HURSIM model has been validated, and the results are described by [Jarvinen et al. \(1991\)](#). [Wang and Vickery \(2005\)](#) state that validation studies compared various storm statistics derived from simulated data with those derived from historical data from 1886–1996 in the National Oceanic and Atmospheric Administration’s (NOAA’s) hurricane database (HURDAT). HURDAT is the official record of tropical storms and hurricanes for the Atlantic Ocean, Gulf of Mexico, and Caribbean Sea, including those that have made landfall in the United States ([NOAA HRD, 2005](#)). Validation results showed that the model was able to reproduce the continuously varying hurricane climatology along the coastline ([Wang and Vickery, 2005](#)).

The **HURricane WiND Field (HURWND) model**, also developed by ARA, provides *estimates of hurricane wind speeds and directions (wind fields)* over the entire storm domain through the use of a finite difference approach on a set of nested rectangular grids. HURWND has been extensively validated by comparing time histories of predicted wind speeds and directions with the corresponding measured data from over 140 anemometers during 15 different hurricanes ([Wang and Vickery, 2005](#)). A description of the model, results, and error statistics from 90 of the validation comparisons are documented by [Vickery et al. \(2000a\)](#).

HURSIM and HURWND are coupled to estimate wind speeds for computation of physical damage, storm surge, and wave modeling. The predictions of hurricane-induced wind speeds as a function of return

period derived from HURSIM define the design-level wind speeds along the Gulf and Atlantic coasts of the United States as defined in the American Society of Civil Engineers “ASCE-7” Standard (1998), the national standard for defining design loads for buildings ([NIBS, 2003](#)).

## 2.2.2 Surge and Wave Models

The HURSIM and HURWIND models are used to estimate the surface wind and atmospheric pressure fields and to provide input to the surge and wave models described below to estimate the potential for coastal flooding induced by hurricanes.

### 2.2.2.1 HURSURGE

The **HURSURGE** model, also developed by ARA, *estimates the rise in the stillwater level associated with hurricane-induced storm surge and astronomical tide*. The model solves the shallow-water (2-D flow) equations of motion using an explicit finite difference method on a series of nested grids. The forcing terms include wind-induced surface stress, bottom friction, atmospheric pressure gradient forces, and direct tide potential from various astronomical tidal constituents. As necessary for accurate astronomical tide predictions ([Mukai et al., 2002](#)), a large analysis grid (i.e., 20 km grid with square cells) covering the Caribbean Sea, the Gulf of Mexico, and the northwestern portion the Atlantic Ocean will be solved initially. Located at the area of interest, a finer-resolution grid (i.e., 2.5 km grid) covering a smaller area will then be solved using the same finite difference model. The analysis will then be repeated with smaller grids (i.e., 500 m grid cells) until the resolution is adequate for capturing the coastal features (e.g., bays, inlets, and barrier islands) at the area of interest. This storm surge model is an advancement of the model described in [Skerlj and Vickery \(1998\)](#).

### 2.2.2.2 WAVEWATCH III

**WAVEWATCH III** is a third-generation wave forecast model for *computing estimates of deepwater wave properties or spectra* that was developed at NOAA’s National Centers for Environmental Prediction (NCEP). WW3 is a further development of the model WAVEWATCH I, developed at Delft University of Technology, and WAVEWATCH II, developed at NASA Goddard Space Flight Center. WW3 nevertheless differs from its predecessors on all important points, such as the governing equations, model structure, numerical methods, and physical parameterizations.

WW3 accounts for wave growth and decay due to surface wind stress, bottom friction, non-linear wave-wave interactions, and wave dissipation. It predicts deepwater wave parameters, such as significant wave height, mean wave period, dominant wave period, mean wave direction, and surface stress acting at the air and water interface ([Wang and Vickery, 2005](#)). The model solves the spectral action density balance equation for wavenumber-direction spectra. The implicit assumption of these equations is that the medium (depth and current) as well as the wave field vary on time and space scales that are much larger than the corresponding scales of a single wave. Furthermore, the physics included in the model do not cover conditions where the waves are severely depth-limited, which implies that the model can generally be applied on spatial scales (grid increments) larger than 1 to 10 km and outside the surf zone ([U.S. Navy, 2003](#)). Two versions of the model have been released: version 1.18 ([Tolman, 1999](#)) and version 2.22 ([Tolman, 2002](#)). Model validation studies using measurements from data buoys during actual hurricane events are described in [Tolman et al. \(2004\)](#) and in [Skerlj et al. \(2000\)](#). This preliminary benchmarking study uses WW3 version 2.22.

WAVEWATCH III models deepwater wave properties until the waves enter shallow water (i.e., approximately 20 percent of the peak wavelength or about a 10 m depth) ([NIBS, 2003](#)). Engineering formulae given in the *Shore Protection Manual* ([USACE, 1984](#)) and in the Simulating Waves Nearshore (SWAN) model are then used for depth-induced wave breaking and wave setup calculations ([NIBS, 2003](#)).

### 2.2.2.3 Simulating Waves Nearshore (SWAN)

SWAN is a third-generation, stand-alone, phase-averaged, numerical, coastal wave model that was developed at the Delft University of Technology. It is used to simulate waves in deep, intermediate, and finite depth waters and to simulate the translation of deepwater waves to nearshore locations ([Wang and Vickery, 2005](#)). It *estimates nearshore wave characteristics, including wave setup, runup, breaker wave heights, and wave periods*. It is also used to obtain realistic estimates of random, short-crested, wind-generated waves for a given bathymetry, wind field, water level, and current field. The SWAN model is also suitable for use as a wave hindcast model. SWAN simulates the following physical phenomena ([WL | Delft Hydraulics, 2005](#)):

- Wave propagation in time and space, shoaling, refraction due to current and depth, and frequency shifting due to currents and nonstationary depth
- Wave generation by wind
- Nonlinear wave-wave interactions (both quadruplets and triads)
- White-capping, bottom friction, and depth-induced breaking
- Blocking of waves by current.

A description of the model and validation results with field data can be found in [Booij et al. \(1999\)](#) and [Ris et al. \(1999\)](#). The model allows the use of nested grids to successively provide high-resolution results at desired locations. SWAN version 40.41 will be nested with WW3 in this project ([Wang and Vickery, 2005](#)).

Validation studies by [Wang and Vickery \(2005\)](#) of project partner ARA compared results from the combined WW3 and SWAN models with measurements from data buoys during several hurricanes. Results revealed that the model provides a good representation of the hurricane wave fields in both deepwater and shallow-water conditions, provided that accurate estimates of hurricane-generated wind fields are available. However, research using WW3 and SWAN continues and further improvements are expected. In addition, the models will be coupled with a coastal dune and beach erosion model, such as the Storm-induced BEACH CHange model (SBEACH) by [Veri-Tech, Inc. \(2005\)](#), to increase the accuracy of the estimated storm damage to the coastal community. SBEACH will not be discussed in this report.

### 2.2.3 HAZUS-MH Loss Estimation Flood Module

In this preliminary benchmarking study, the surge-only water levels from HURSURGE and the water levels obtained by adding wave setup values from WW3 coupled with SWAN to surge values (surge-plus-wave-setup) were input into the HAZUS-MH MR1 flood module to determine losses before and after the use of WW3. The following module description was taken directly from the FEMA HAZUS-MH flood module Web site as it existed on July 22, 2005:

Two modules—flood hazard analysis and flood loss estimation analysis—carry out the basic analytical processes that comprise the flood loss estimation methodology. The flood hazard analysis module uses characteristics such as frequency, discharge, and ground elevation to estimate flood depth, flood elevation, and flow velocity. The flood loss estimation module calculates physical damage and economic loss from the results of the hazard analysis. The results are displayed in a series of reports and maps.

The HAZUS-MH flood module operates at the census block level. There are three levels of analysis that are available to users in the HAZUS-MH flood module. As noted below, the required input data and expertise vary according to the level of analysis:

- Level 1: All of the information needed to produce a basic estimate of local flood losses is included as default data, based on national databases and nationally applicable methods.
- Level 2: More detailed input data will be needed, including detailed information on local conditions. Modification of default databases will be required, along with the inclusion of local data and analyses.
- Level 3: Detailed and site-specific input data are used to create state-of-the-art damage estimates and situation assessment profiles. Level 3 is intended for the expert user.

The Flood Information Tool (FIT), released in 2002, is designed to process locally available flood information and convert it into data that can be used by the HAZUS-MH flood module. The FIT is a system of instructions, tutorials, and GIS analysis scripts. When provided with user-supplied inputs (e.g., ground elevations, flood elevations, and floodplain boundary information), the FIT calculates flood depth and elevation for riverine and coastal flood hazards. The FIT is intended to help users perform Level 2 or Level 3 flood hazard analyses. The user is allowed to input various combinations of data (i.e., default data provided with the model and community-specific data provided by the user) to customize the analysis ([FEMA, 2005](#)).

More information about the version of the HAZUS-MH flood module used in this study as well as information about its continuing development can be found in the results and discussion section of this report (Section [4.0](#)).

### 3.0 Methodology for Preliminary Benchmarking Activity

This particular benchmarking activity is unique in that the product being benchmarked was still under development at the time of this study. The incorporation of the WW3 model into HAZUS-MH and the completion of the HAZUS-MH flood module (to take full advantage of the use of results from WW3 and the other planned improvements) are not scheduled for completion and public release until 2008. Hence, this activity may be viewed as a proof-of-concept or as a feasibility step. These interim steps are necessary and valuable to ensure that proper emphasis and direction are considered as the module continues to be developed and as WW3 is integrated into HAZUS-MH over the next two years.

Conceptually, the methodology for this preliminary benchmarking study is quite simple:

- Run the HAZUS-MH coastal flood module and replace the 100-year stillwater elevations with the following modeled inundation levels in each study area:

- Inundation levels resulting from “surge-only” from the HURSURGE model; represents baseline conditions (current methodology)
- Inundation levels resulting from “surge-plus-wave-setup” obtained by adding wave setup from the WW3 model coupled with the SWAN model (deepwater wave properties modeled with WW3; nearshore, shallow wave properties modeled with SWAN) to surge-only values; represents “improved” methodology
- Qualitatively compare the extent of inundation and economic loss parameters resulting from surge-only and surge-plus-wave-setup cases to determine change in modeled coastal hazard losses.

Specifically, the following baseline HAZUS model parameters were used for all study areas:

- Software version: HAZUS-MH MR1 (released January 2005)
- Building stock: HAZUS default, as contained in the HAZUS database for the study areas (based on U.S. Census 2000 data with cost averages from an evaluation performed in 2001–2002)
- Storm event: Hurricane Ivan (which made landfall on September 16, 2004) with storm track and parameters as defined by ARA
- Digital Elevation Model (DEM): HAZUS default (U.S. Geological Survey (USGS) National Elevation Dataset (NED) (30-m resolution))
- Shoreline characteristics: HAZUS default (simplified coastline)
- Transects: to be determined by the model

The following storm surge model (HURSURGE) parameters were used for all study areas:

- Grid resolution: 500 m (consistent with the finest resolution from the Sea, Land, and Overland Surges from Hurricanes (SLOSH) model used by FEMA contractors)
- Bathymetry: HAZUS default (National Geophysical Data Center’s (NGDC) datasets)
  - Deepwater: NGDC ETOPO2 2-minute grid resolution data ([NGDC, 2005a,b](#))
  - Nearshore: 3-arc-second (~90 m) NGDC coastal relief dataset ([NGDC, 2005c](#))
- Tide model: implemented (thus, tide effects are included in storm surge elevations)
- Surge model outputs: stillwater elevations (in meters) at each transect location

The following wave model parameters were used for all study areas:

- Deepwater waves: determined by WW3 version 2.22 driven by the Hurricane Ivan storm track; used 20-km resolution grids to cover the study area.
- Shallow-water waves: determined by SWAN version 40.41 driven by WW3 and the Hurricane Ivan storm track; SWAN uses three 100-m resolution grids to cover the study area.
- Wave model outputs: wave setup at each transect location; wave elevation at each transect

The methodology had some significant limitations in the version of HAZUS-MH used in this study:

- HAZUS-MH MR1 flood module is not set up for performing scenario analyses (i.e., for a particular set of detailed storm parameters). Instead, the module performs probabilistic analyses; in this case, a 100-year storm was selected and modified to represent the conditions produced by Hurricane Ivan.



- HAZUS-MH MR1 flood module accepts only one stillwater elevation (as opposed to a grid of values), and thus the stillwater surface affects the *entire* study region.
  - Maximum stillwater elevation is propagated everywhere within the study area where the ground elevation is lower than the flood elevation and is hydraulically connected to the flood source.
  - Method is appropriate only for very small study regions (i.e., areas with relatively constant/consistent stillwater elevation)
- Wave setup model in HAZUS-MH MR1 decays the wave setup over barrier islands and does not regenerate it over inland fetches. To better model the effect of wave setup, the height of wave setup calculated by SWAN was added directly to the surge elevation at the coast, and the wave setup model within HAZUS-MH was turned off.
- 30-meter DEMs from USGS
- Default simplified coastline (ignores smaller bays, etc.)

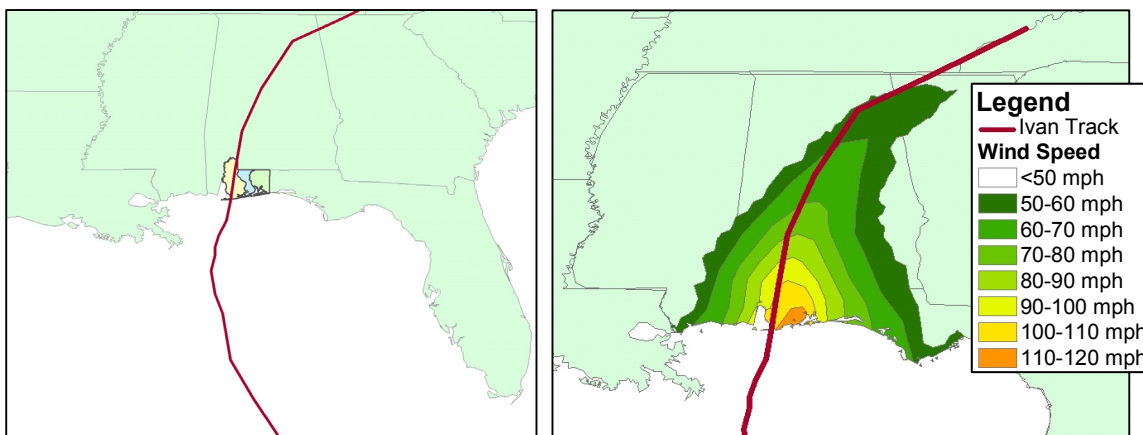
Because this study was conducted when the product was still under development, it is suggested that a more thorough benchmarking analysis be performed in 2008 when all models (such as WW3, SWAN, and HURSURGE) have been successfully coupled and integrated into HAZUS-MH. When development is complete, the HAZUS-MH wind and coastal flood models will be seamlessly integrated to estimate wind and flooding losses from hurricanes. Results can then be compared to validation data to determine the extent of the improvements gained by integrating WW3 and the other models.

### 3.1 Study Region and Test Case

Because only one stillwater elevation for surge-only and for surge-plus-wave-setup is used for the entire study region in the HAZUS-MH MR1 flood module (which is still under development), study areas with relatively consistent levels of surge-only and surge-plus-wave-setup across each shoreline area must be chosen. In addition, to determine the improvements gained by incorporating wave setup with surge instead of using surge alone, validation data (i.e., an area with measured levels of inundation due to tropical storm or hurricane forces) is eventually needed with which to compare inundation levels from surge-only and surge-plus-wave-setup modeled responses. The 2004 hurricane season provided many opportunities to develop a validation dataset in the eastern part of the Gulf of Mexico. The study region selected for this exercise was along the Alabama/Florida border where Hurricane Ivan made landfall as a Category 3 hurricane on September 16, 2004.

According to the National Hurricane Center, Ivan was a classical, long-lived Cape Verde hurricane that reached Category 5 strength three times on the Saffir-Simpson Hurricane Scale (SSHS). It was also the strongest hurricane on record (as of June 2005) that far southeast of the Lesser Antilles. Ivan caused considerable damage and loss of life as it passed through the Caribbean Sea. Ivan made landfall as a 105-knot hurricane (Category 3 on the SSHS) at approximately 0650 UTC (coordinated universal time) on September 16, 2004, just west of Gulf Shores, AL. By this time, the eye diameter had increased to 40-50 nautical miles, resulting in some of the storm's strongest winds occurring over a narrow area near the southern Alabama/western Florida panhandle border. After Ivan moved across the barrier islands of Alabama, the hurricane turned north/northeastward across eastern Mobile Bay and weakened into a tropical storm 12 hours later over central Alabama. The full report on Ivan is archived on the National Weather Service's Web site ([Stewart, 2005](#)).

Ivan's path and estimated wind field are shown in [Figure 2](#). Hurricane force winds extended 105 miles outward from the center of the eye. Extreme storm surge conditions extended along a 90-mile length of the open coast, reaching 5 miles west and 85 miles east of the hurricane track ([FEMA, 2004b](#)).



**Figure 2.** Hurricane Ivan's storm track as it relates to the study region and estimated wind field (3-second gust wind speeds in mph).

Using high water marks and debris lines, FEMA created a surge inundation limit map against which preliminary results from this benchmarking analysis can be qualitatively compared. The inundation limit represents the inland extent of flooding caused by storm surge. FEMA first identified and surveyed coastal high water marks (including mud lines, water stains, debris, and eye witness testimony) using GPS methods. A report generated by [FEMA \(2004b\)](#) stated that the measured coastal high water marks *include the effects of wave setup along with storm surge*. However, every attempt was made by the survey teams to identify and note when *wave heights* and *wave runup* may have also been captured with the storm surge elevation at the high water mark location. The surge inundation limit map was created by mapping surveyed high water marks (that were known to *not* contain the effects of *wave heights*) to digital, pre-storm topographic contour data. Debris lines were mapped based upon interpretation of digital, color aerial photography acquired by the U.S. Army Corps of Engineers a few days after the storm. Engineering judgment was used to interpolate the inundation limit in areas where elevations of closely spaced high water marks differed significantly and to adjust the inundation limit to the debris line. As an interesting side note, FEMA-derived surge elevations from Hurricane Ivan cannot be directly compared to BFEs on FEMA Flood Insurance Rate Maps (FIRMs), because BFEs in coastal areas include both storm surge and wave effects (here, wave heights and runup) ([FEMA, 2004a,b](#)).

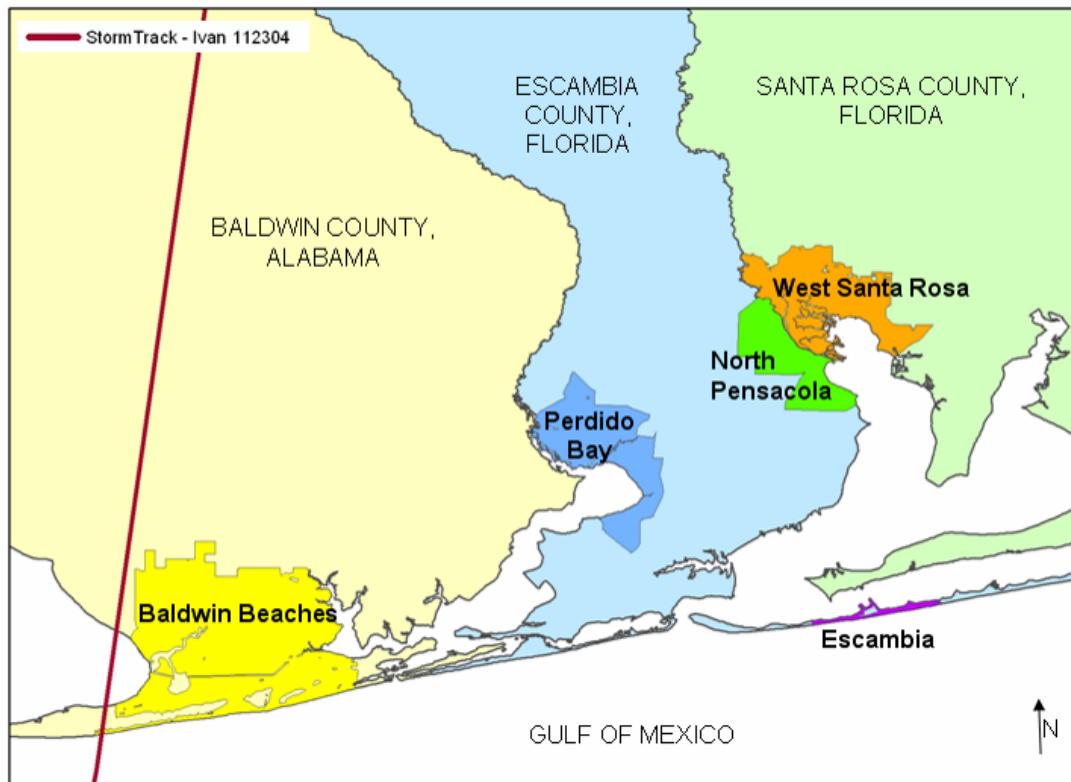
Five small study areas with relatively consistent levels of surge-only and surge-plus-wave-setup across each area were chosen for this analysis. The Hurricane Ivan landfall scenario provided validation data for these five case studies in two states, in three counties, and in a variety of coastal situations (two barrier islands, sheltered bays, etc.). The five study areas selected for this preliminary benchmarking activity were as follows:

- Baldwin Beaches—the beach areas of Baldwin County, AL; protected by barrier islands.
- Escambia Beach—barrier island beach area off the coast of Escambia County, FL; open to the Gulf of Mexico.
- West Santa Rosa—east side of Escambia Bay in Santa Rosa County, FL; protected by barrier islands and at the far end of a bay.



- North Pensacola—protected area on west side of Escambia Bay, east side of Escambia County, FL; protected by barrier islands and at the far end of a bay.
- Perdido Bay—area on west side of Escambia County, FL; protected by barrier islands and at the far end of a bay.

These sites are shown in geographic context in [Figure 3](#).



**Figure 3.** Study areas.

The Baldwin Beaches study area is 79 square miles in size, contains 544 census blocks, and has a total population of approximately 12,900 people (according to HAZUS-MH default data from the 2000 U.S. Census). The shoreline could be described as a sandy beach with small dunes (thus, dune erosion is being considered in the model) with open wave exposure. The region contains an estimated total of 7,650 buildings with a total building replacement value (excluding contents) of approximately \$1,341 million (in 2002 dollars). Residential housing comprises approximately 98 percent of the buildings and approximately 85 percent of the building value.

The Escambia Beach study area is a barrier island that is 2 square miles in size, contains 78 census blocks, and has a total population of fewer than 2,500 people (according to HAZUS-MH default data from the 2000 U.S. Census). The region contains an estimated total of 1,465 buildings with a total building replacement value (excluding contents) of approximately \$305 million (in 2002 dollars). Residential housing comprises approximately 99 percent of the buildings and approximately 93 percent of the building value.

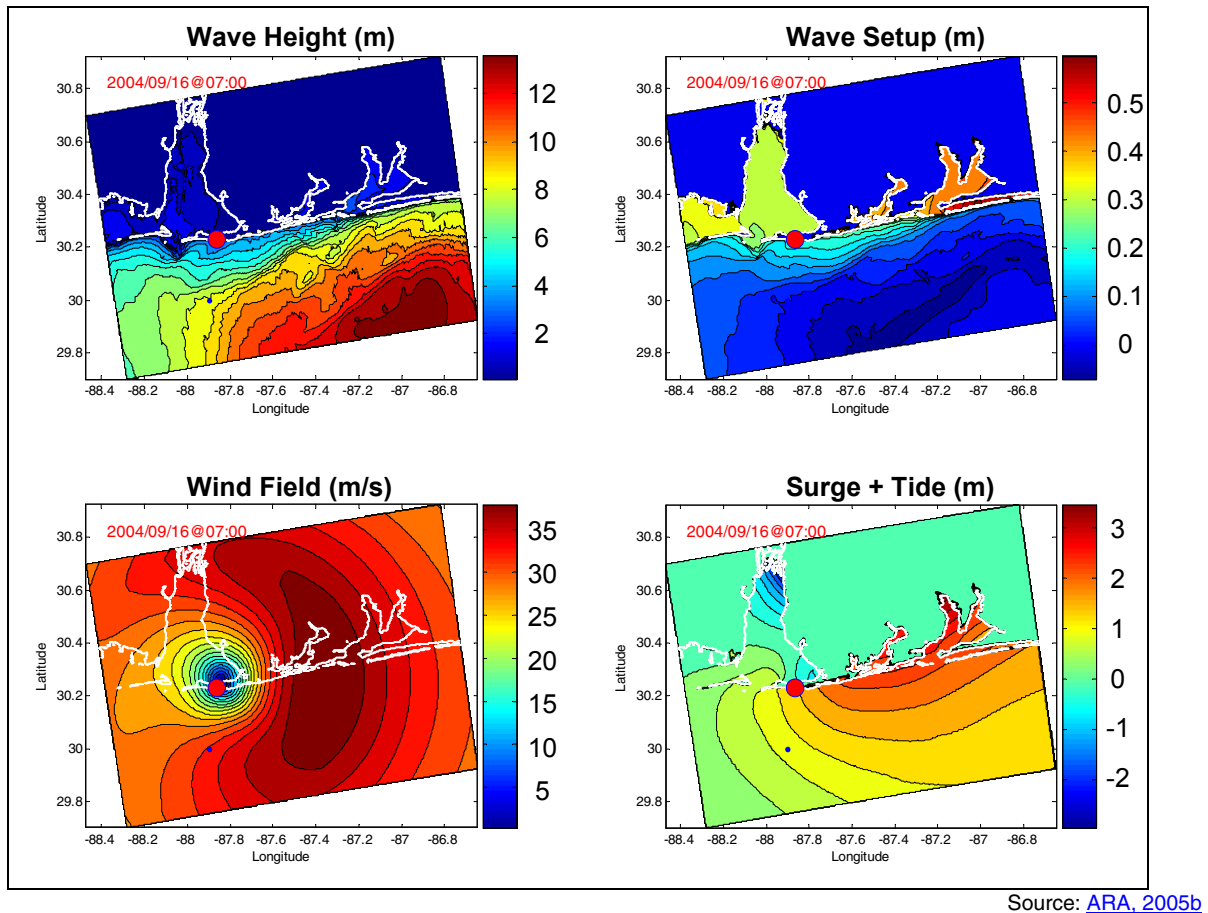
The West Santa Rosa study area is 29 square miles in size, contains approximately 185 census blocks, and has a total population of about 11,000 people (according to HAZUS-MH default data from the 2000 U.S. Census). The region contains an estimated total of 4,000 buildings with a total building replacement value (excluding contents) of approximately \$478 million (in 2002 dollars). Residential housing comprises approximately 99 percent of the buildings and approximately 86 percent of the building value.

The North Pensacola study area is 17 square miles in size, contains 238 census blocks, and has a total population of greater than 24,000 people (according to HAZUS-MH default data from the 2000 U.S. Census). The region contains an estimated total of 8,450 buildings with a total building replacement value (excluding contents) of approximately \$1,438 million (in 2002 dollars). Residential housing comprises approximately 99 percent of the buildings and approximately 83 percent of the building value.

The Perdido Bay study area is 27 square miles in size, contains 65 census blocks, and has a total population of greater than 6,000 people (according to HAZUS-MH default data from the 2000 U.S. Census). The region contains an estimated total of 2,440 buildings with a total building replacement value (excluding contents) of approximately \$324 million (in 2002 dollars). Residential housing comprises approximately 99 percent of the buildings and approximately 90 percent of the building value.

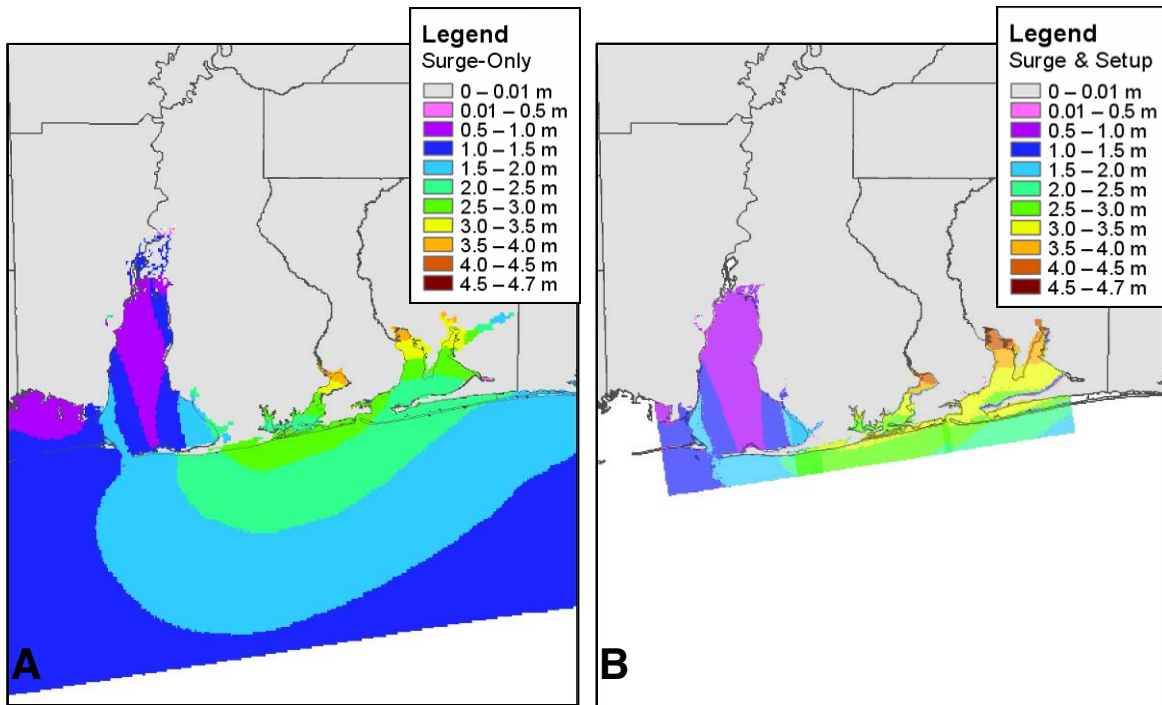
### **3.2 Model Inputs**

[Figure 1](#), shown earlier in the report, depicts the dataflow through the HAZUS-MH MR1 model at the time of this study. The modeled wind field (in meters per second) is generated by the HURWIND model. The wind field is used in the HURSURGE model to produce surge values (in meters), which include the effects of tide (although referred to as “surge-only” in this report). The wind field is also used in the WW3 model coupled with the SWAN model to generate wave properties, such as wave height (in meters), and to produce wave setup (in meters). The wave setup output from WW3/SWAN is then added to the surge-only value to obtain the surge-plus-wave-setup value. Some of these modeled datasets are shown in [Figure 4](#) for one of the modeling time steps (in this case, when Hurricane Ivan made landfall).

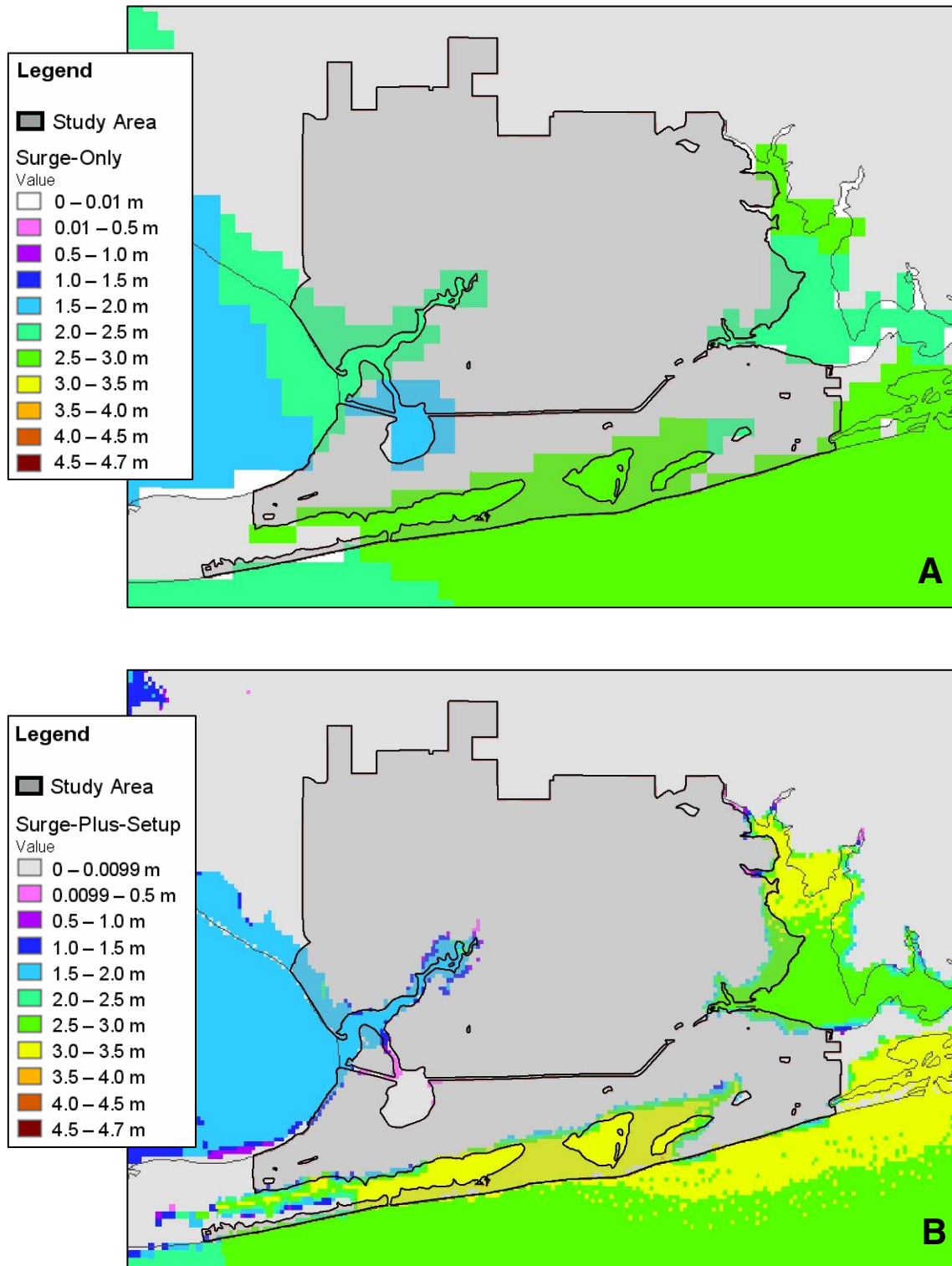


**Figure 4.** Modeled wind speeds (valid for marine exposure), wave, and surge values from Hurricane Ivan.

Values of surge-only (produced by the HURSURGE model) and surge-plus-wave-setup (wave setup produced by the WW3 and SWAN models and added to surge-only) are then input into the HAZUS-MH MR1 loss estimation flood module. When this preliminary benchmarking activity was performed, inputs to the HAZUS-MH MR1 flood module included a single water elevation for surge-only and for surge-plus-wave-setup for each study area. The surge-only and surge-plus-wave-setup datasets used in this study are shown in [Figure 5](#) for the entire study region. [Figure 6](#) contains a zoomed-in view of these datasets for one of the five study areas, Baldwin Beaches. The surge-plus-wave-setup values (shown in [Figure 6B](#)) are roughly 0.5 meters (around 1 foot) higher than the surge-only values for the Baldwin Beaches study area. Similar figures for the remaining four study areas are provided in [Appendix A](#).



**Figure 5.** Water elevations as a result of surge-only (A) and surge-plus-wave-setup (B). Units are in meters.



**Figure 6.** Comparison of surge-only (A) and surge-plus-wave-setup (B) for Baldwin Beaches study area.

The single flood elevation or stillwater elevation values used in the HAZUS-MH flood module were obtained by querying the surge-only and surge-plus-wave-setup datasets along the shoreline (in ESRI® ArcGIS®) for each study area and by generally averaging the values for each case scenario (i.e., surge-only or surge-plus-wave-setup). The stillwater elevations that were used as input values in this analysis for all five study areas are listed in [Table 1](#). Values are given in feet and in meters because HURSURGE and WW3/SWAN produce values in meters, but the HAZUS-MH MR1 flood module uses values in feet.

**Table 1.** Averaged surge-only and surge-plus-wave-setup values used as input to the HAZUS-MH MR1 flood module for the five study areas.

Study area	Surge-Only	Surge-Plus-Wave-Setup
Baldwin Beaches	9 ft (between 2.5 and 3.0 m)	10 ft (between 3.0 and 3.5 m)
Escambia Beach	7.5 ft (between 2.0 and 2.5 m)	8.5 ft (between 2.5 and 3.0 m)
West Santa Rosa	12.5 ft (between 3.5 and 4.0 m)	15 ft (between 4.5 and 4.7 m)
North Pensacola	11 ft (between 3.0 and 3.5 m)	14 ft (between 4.0 and 4.5 m)
Perdido Bay	11.5 ft (between 3.0 and 4.0 m)	13 ft (between 3.5 and 4.5 m)

## 4.0 Results and Discussion

For each of the five case study areas, the HAZUS-MH MR1 flood module was run, replacing the 100-year stillwater elevation with a single flood elevation value for surge-only and for surge-plus-wave-setup, to show the economic impact as a result of adding wave setup to surge (and thus the benefit of eventually integrating WW3 and SWAN with HAZUS-MH). The following results for the Baldwin Beaches study area are shown in [Figure 7](#):

- a digital elevation model of the study area;
- a comparison of the depth grids (in feet) generated by the HAZUS-MH MR1 flood module showing the extent of flooding resulting from inputting single values for surge-only and for surge-plus-wave-setup into the version of the HAZUS-MH flood module that was publicly available at the time of this study; and
- a preliminary comparison of these flooding extents to the inundation limit map developed by FEMA.

Similar figures for the remaining four study areas can be found in [Appendix A](#).

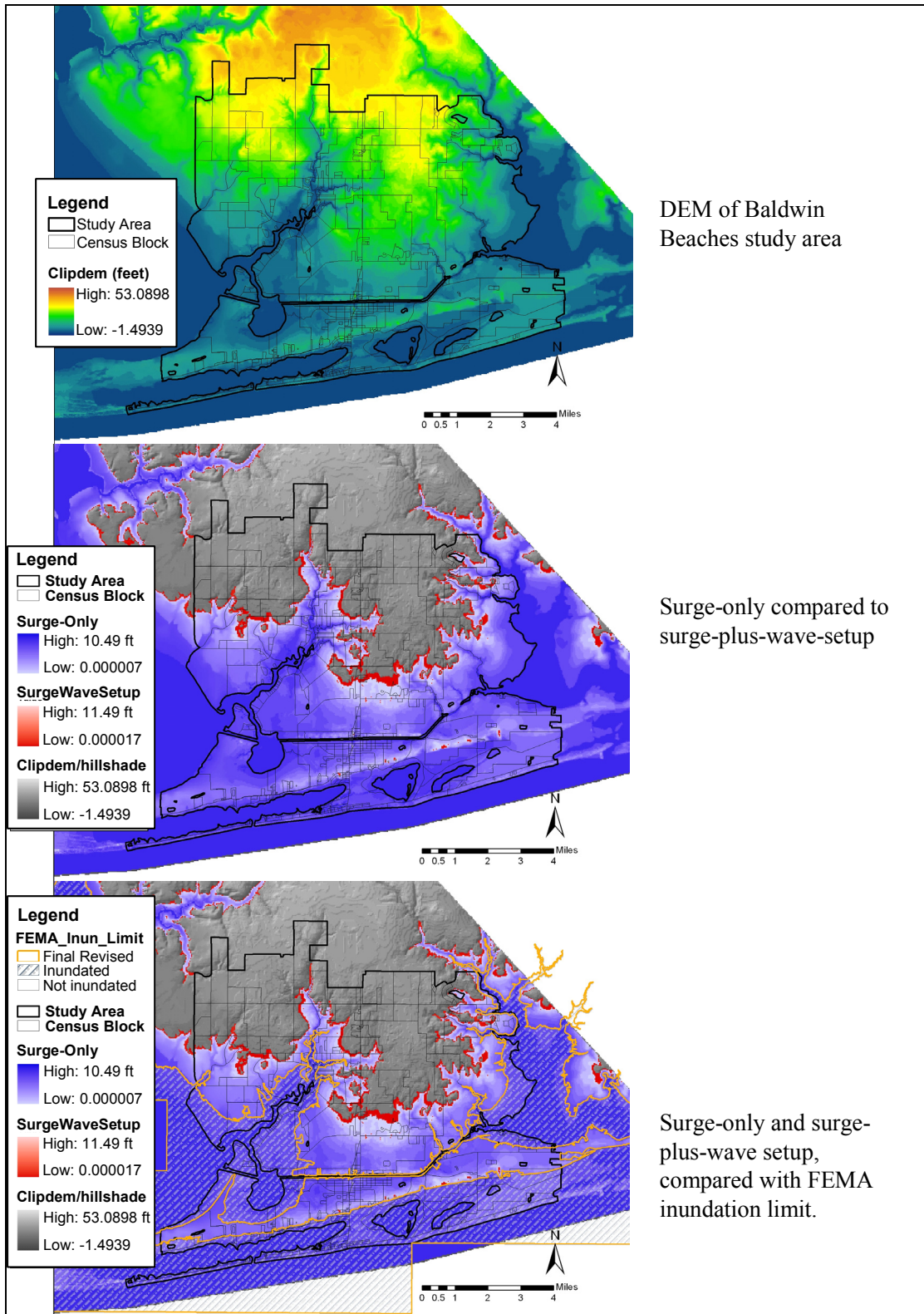
In [Figure 7](#), the DEM shows that the majority of the Baldwin Beaches study area consists of low-lying terrain. The surface slopes very gradually to the shoreline, which is protected by barrier islands. Because of the terrain's gradual slope and low-lying nature, the flooding extents from both the surge-only and from the surge-plus-wave-setup case scenarios extend far inland. The surge-plus-wave-setup flood extent (shown in red) exceeds the surge-only extent (shown in blue). The barrier islands of this study area are shown to be completely inundated both by the surge-only and by the surge-plus-wave-setup case scenarios, which agrees with what was mapped in the FEMA inundation limit. In general, FEMA reported that ground truth data indicated that many of the barrier islands in the hardest hit areas were overtopped and that the sand dunes either no longer remain or were inundated. Therefore, these barrier islands were generally shown as completely inundated on the inundation limit maps ([FEMA, 2004b](#)). [Figure 7](#) also

shows that the flooding extents both from surge-only and from surge-plus-wave-setup exceed the FEMA inundation limit (shown in orange and included merely as a point of reference for qualitative comparison).

When reviewing these results, the reader should keep in mind that the HAZUS-MH flood module was still under development at the time of the study. In the HAZUS-MH MR1 flood module, the depth grids are generated by overlaying one user-supplied stillwater elevation onto the DEM for the surge-only and for the surge-plus-wave-setup case scenarios. In the Baldwin Beaches study area, the stillwater elevation used in the HAZUS-MH MR1 flood module for surge-only was 9 feet and for surge-plus-wave-setup was 10 feet. Therefore, the extent of flooding for the Baldwin Beaches study area for surge-only and for surge-plus-wave-setup generally represents a 9-ft and 10-ft contour, respectively. This also means that the flood depths (in red in the figures) from surge-plus-wave-setup that extend beyond the surge-only generated depths (shown in blue) are 1 foot or less in depth for the Baldwin Beaches study area. The HAZUS-MH MR1 flood module did not take into account the effect of wind pushing waves inland as storms came onshore or the retarding effect of obstacles on the inland flow of water, which could explain the overestimation of the modeled flooding extent when compared to the FEMA inundation limit as seen in [Figure 7](#) for the Baldwin Beaches study area. These conditions (i.e., wind effects and friction caused by land and by obstacles) would obviously have played a role in how far inland the storm surge traveled, and thus would have been reflected in the FEMA inundation limit validation data created from high water marks. In addition, the use of only one value for flood depth in the HAZUS-MH MR1 flood module instead of a grid of variable flood depths also would obviously affect the results significantly. For these reasons, detailed agreement between modeled results from the HAZUS-MH MR1 flood module and measured results (i.e., FEMA inundation limits) is not expected; however, there should be general agreement between measured results and modeled results.

When development is complete, the HAZUS-MH wind and coastal flood models will be seamlessly integrated to estimate wind and flooding losses from hurricanes. When this integration occurs, many of the abovementioned issues will be resolved, and future validation and benchmarking studies should show closer comparisons to validation data and increased accuracy of results.





**Figure 7.** DEM of Baldwin Beaches study area, resulting inundation extent from inputting water elevation value for surge-only and surge-plus-wave-setup cases into HAZUS-MH MR1 flood module, and comparison of these inundation extents with FEMA inundation limit. Units are in feet.



In addition to the depth grids, such as the ones shown in [Figure 7](#) for surge-only and surge-plus-wave-setup, the HAZUS-MH flood module also generates a “flood event summary report” containing a variety of information: a general description of the study region, a building inventory, and estimates of social and economic impact or loss. Loss is stated in terms of the total economic loss estimated for the flood, which includes building-related losses. Building-related losses include direct building losses and business interruption losses. The *direct building losses* are the estimated costs to repair or replace the damaged areas of the building and its contents. The *business interruption losses* are the estimated losses associated with the inability to operate a business because of the damage sustained during the flood. Business interruption losses also include the estimated temporary living expenses for those people displaced from their homes because of the flood. [Table 2](#) contains the key economic loss parameters for each case scenario (i.e., for surge-only and surge-plus-wave-setup) for each study area. Other selected economic and social loss parameters generated by the HAZUS-MH flood module for all study areas are provided in [Appendix B](#). Percent difference in total economic loss is also included in [Table 2](#), which was calculated using the following formula:

$$\text{Percent Difference} = \frac{|measure_1 - measure_2|}{\left(\frac{measure_1 + measure_2}{2}\right)} * 100$$

**Table 2.** Results generated by the HAZUS-MH flood module for each study area and each test case.

Study Area	Test Case	Average Total Building Replacement Value (in millions)*	Total Economic Loss Estimated for Flood (in millions)	Percentage of Total Replacement Value of Region's Buildings	Difference in Total Economic Loss (in millions)	Percent Difference in Total Economic Loss
Baldwin Beaches	Surge-only	\$1341	\$546.1	~41	\$89.7	15
	Surge-plus-wave-setup		\$635.76	~47		
Escambia Beach	Surge-only	\$305	\$142.37	~47	\$46.8	28
	Surge-plus-wave-setup		\$189.12	~62		
West Santa Rosa	Surge-only	\$478	\$16.35	~3	\$13	57
	Surge-plus-wave-setup		\$29.36	~6		
North Pensacola	Surge-only	\$1438	\$33.68	~2	\$22	49
	Surge-plus-wave-setup		\$55.72	~4		
Perdido Bay	Surge-only	\$324	\$78.33	~24	\$29.8	32
	Surge-plus-wave-setup		\$108.15	~33		

\* Total building replacement value (excluding contents) (2002 dollars)

For every study area, adding wave setup to surge-only values resulted in increased estimated damage, ranging from an additional \$13 million to \$90 million in total economic loss. Percent differences between total economic loss estimates from surge-only and from surge-plus-wave-setup ranged from 15 to 57 percent for these study areas, thus indicating the change resulting from adding wave setup to surge.

Baldwin Beaches is the largest of the study areas (79 square miles) and has the second highest average total building replacement value (\$1341 million). The additional one-foot increase in water level (from 9 to 10 feet) when wave setup was added resulted in an additional \$90 million in estimated damage—the highest difference in total economic loss for these five study areas. The loss estimates for Baldwin Beaches also represented the second highest percentage of the total replacement value of the region's buildings, ranging from 41 percent for surge-only to 47 percent for surge-plus-wave-setup. Much of the study area was estimated to be flooded (by the version of HAZUS that was used for this study) because of the terrain's low-lying nature and its gradual slope to the coast (as seen in the DEM in [Figure 7](#)). Even though many people's homes and businesses were affected by this storm, the difference between surge-only and surge-plus-wave-setup (as indicated by the 15 percent difference in total economic loss) for the Baldwin Beaches study area was the lowest of all the study areas. In this study, Baldwin Beaches had the least amount of change between total economic loss from surge-only and from surge-plus-wave-setup.

The study area with the largest percent difference in total economic loss (57 percent) when comparing loss estimates from surge-only and from surge-plus-wave-setup was West Santa Rosa. Only a small portion of the developed part of this 29-square-mile study area was estimated to be damaged by flooding (by the version of HAZUS used in this study). The total economic loss from surge-only and from surge-plus-wave-setup represented 3 percent and 6 percent, respectively, of the total building replacement value (\$478 million). When wave setup was added to surge a 2.5-foot increase in water level (from 12.5 to 15 feet) resulted in an additional \$13 million in estimated damage, the lowest difference in total economic loss for these five study areas. A large area in the northwest portion of the study area was flooded (as seen in [Figure A-4, Appendix A](#)), but the area is covered by wetlands and is largely undeveloped, and thus would not factor into the economic loss estimates.

The percent difference indicates the change in damage estimates as a result of adding wave setup to surge values, and thus the importance of this work to incorporate WW3 and other models into HAZUS to better model coastal flooding as a result of hurricanes. However, the true importance of including wave setup with surge cannot be fully shown until the models are fully integrated and development is complete. At that time, the results can be validated against real-world observations to show the expected increase in accuracy in flood loss estimates gained by adding wave setup to surge-only values through the integration of WW3 into HAZUS-MH.

## 5.0 Preliminary Conclusions

This preliminary benchmarking activity was performed to determine potential improvements in loss estimates generated by the HAZUS-MH MR1 flood module as a result of the integration of WW3 model results into the modeling process. HAZUS-MH MR1 uses water levels produced by storm surge models only. By integrating the WW3 model coupled with the SWAN model into future versions of HAZUS-MH, wave setup can be added to surge values to obtain a more realistic water level for coastal flooding as storms make landfall. These more accurate flood elevations that include wave setup with surge are expected to improve loss estimates generated by the HAZUS-MH flood module.

This benchmarking activity was conducted in the coastal Alabama/Florida Panhandle region in five study areas. Surge-only values were modeled for Hurricane Ivan using the HURSURGE model. Wave setup values were modeled for Hurricane Ivan using the WW3 model (coupled with the SWAN model) and then added to surge-only values to obtain surge-plus-wave-setup values. HURSURGE, WW3, and SWAN have all been separately validated by various researchers. These values for surge-only and for surge-plus-wave-setup were then entered into the HAZUS-MH MR1 flood module to obtain loss estimates. In each of the five study areas, adding the wave setup to the surge-only output predicted greater depths of water—

from 1 to 3 feet. The increased flood depth estimates translated into greater economic loss estimates (as expected). The increases in total economic loss estimates ranged from \$13 million to \$90 million for the five study areas. Percent differences between total economic loss estimates from surge-only and from surge-plus-wave-setup ranged from 15 percent to 57 percent for these study areas, thus indicating the change resulting from adding wave setup to surge.

The FEMA inundation limits were used to verify that the modeled results were reasonable. The FEMA inundation limit had little detailed agreement with the depth grids and flooding extents generated by the HAZUS-MH MR1 flood module when values of surge-only and of surge-plus-wave-setup were entered to calculate damage loss estimates, primarily because the HAZUS-MH flood module is currently still under development. At the time of this study, the HAZUS-MH MR1 flood module generated the flooding depth grids and extents by overlaying a single user-supplied value or stillwater elevation for the surge-only or for the surge-plus-wave-setup cases on a DEM to determine which areas were inundated and thus which buildings would have been flooded/damaged. When determining areas of inundation and damage estimates, the model at the time of the study did not yet take into account the retarding effect of the ground surface (“land friction”), buildings, or other obstacles (“form friction”) on the flow of water as it moved inland, or the effect of wind pushing waves further inland when storms made landfall. These conditions (i.e., wind effects and friction caused by land and obstacles) would obviously have affected the flooding extent during the event (captured in the FEMA inundation limit validation data), thus providing an explanation for the overestimation of the modeled flooding extent. In addition, the use of only one value for flood elevation in the HAZUS-MH MR1 flood module instead of a grid of variable flood elevations also obviously would have affected the results significantly.

In summary, it must be stressed that this benchmarking study is preliminary because when the study was performed, the storm surge and wave models (such as WW3 and SWAN) were not fully coupled and integrated into HAZUS-MH, and the HAZUS-MH flood module was still under development. The approach taken in this study is consistent with the approach a user of HAZUS-MH MR1 would have to take to perform a scenario coastal study. Still, the results from this preliminary study are very promising. This was an excellent opportunity to gauge preliminary results with real-world events—to demonstrate the potential improvements in loss estimates by incorporating wave setup with storm surge through the use of WW3 and to demonstrate the feasibility of the HAZUS-MH flood module to provide reliable information to coastal resource managers and emergency planners.

Several physical parameters are still being integrated into HAZUS-MH, including the effect of wind on the waves, land and form friction (obstacles to water flow), and more accurate terrain and bathymetry. The major integration step includes fully coupling HURSURGE, WW3, and SWAN to produce estimates of stillwater elevation rise and wave heights that better model the physical process. As each of these parameters and surge/wave models are integrated into HAZUS-MH, an improved and more robust model product would be expected, yielding more accurate results. When development is complete, the HAZUS wind and coastal flood models will be seamlessly integrated to estimate wind and flooding losses from hurricanes. When this enhanced version of HAZUS-MH is released to the public in 2008, a more comprehensive benchmark analysis will need to be performed. Model results before and after the full integration of WW3 can then be compared with real-world validation data to determine the magnitude/extent of the improvements to loss estimates. These improved loss estimates can then be more fully utilized by planners and responders to mitigate and prevent loss of life and property as a result of hurricanes.

## 6.0 References

- ASCE [American Society of Civil Engineers], 1998. *Minimum Design Loads for Buildings and Other Structures*, ASCE-7 Standard. Reston, VA.
- ARA [Applied Research Associates], 2005a. *Introduction to HAZUS-MH Flood Model*. Unpublished presentation, April 28.
- ARA, 2005b. *Nearshore Wave and Beach Erosion Modeling*. Unpublished presentation, April 28.
- ARA, 2005c. *Storm Surge Model: Hurricane Ivan Simulation for Baldwin-Escambia Coastal Region*. Unpublished presentation, April 28.
- Booij, N., R. C. Ris, and L. H. Holthuijsen, 1999. A third-generation wave model for coastal regions, 1. Model description and validation. *Journal of Geophysical Research*, 104(C4): 7649–7666.
- Booij, N., I. J. G. Haagsma, L. H. Holthuijsen, A. T. M. M. Kieftenburg, R. C. Ris, A. J. van der Westhuysen, and M. Zijlema, 2004. *SWAN Cycle III Version 40.41: User Manual*. Delft University of Technology, The Netherlands. 115 p.  
<http://fluidmechanics.tudelft.nl/swan/download/zip/manuals.zip>, accessed 1/31/06.
- FEMA [Federal Emergency Management Agency], 2004a. *Notes to Users of Hurricane Ivan Surge Inundation Maps*. <http://www.fema.gov/ivanmaps/pdf/notestousers.pdf>, accessed 8/20/05.
- FEMA, 2004b. *Hurricane Ivan Surge Inundation Maps: Summary of Methods*. Contract No. EMW-2000-CO-0247; Task Order Nos. 351 (FL) and 352 (AL). December 6. 11 p.  
[http://www.fema.gov/ivanmaps/pdf/Ivan\\_Summary\\_of\\_Methods.pdf](http://www.fema.gov/ivanmaps/pdf/Ivan_Summary_of_Methods.pdf), accessed 8/20/05.
- FEMA, 2005. *Multi-Hazards: HAZUS Loss Estimation Flood Model*.  
[http://www.fema.gov/hazus/hz\\_flood.shtm](http://www.fema.gov/hazus/hz_flood.shtm), accessed 7/22/05.
- Jarvinen, B. R., C. J. Neumann, and M. A. S. Davis, 1991. *A Tropical Cyclone Data Tape for the North Atlantic Basin 1886-1983: Contents, Limitations, and Uses*. Technical Memorandum NWS-NHC-22, National Oceanic and Atmospheric Administration, Washington, DC.
- Lavelle, F., 2005. *Future of HAZUS-MH: Updates to the Software and Technical Methodology*. Third Annual Southeastern HAZUS User Group Conference (SEHUG), Charleston, SC, March 8, 2005.
- Mukai, A. Y., J. J. Westerink, and R. A. Luettich, 2002. *Guidelines for Using East Coast 2001 Database of Tidal Constituents within Western North Atlantic Ocean, Gulf of Mexico and Caribbean Sea*. ERDC/CHL CHETN-IV-40, U.S. Army Corps of Engineers, Coastal and Hydraulics Engineering Technical Note, March, 20 p. <http://chl.erd.usace.army.mil/library/publications/chetn/pdf/chetn-iv-40.pdf>, accessed 1/31/06.
- NASA [National Aeronautics and Space Administration], 2003. *Decision Support Tools Evaluation Report for HAZUS-MH<sup>®</sup> Hurricane Model, Version 1.0*. Earth Science Applications Directorate,

- HAZUS-MH DST Evaluation Team, October 22. 66 p.  
<http://aiwg.gsfc.nasa.gov/esappdocs/evalreports/HAZUSMHEval04.doc>, accessed 1/31/06.
- NASA, 2004. *NASA Earth Science Applications Plan*. NP-2004-08-368-HQ. Office of Earth Science, 104 p. <http://science.hq.nasa.gov/strategy/AppPlan.pdf>, accessed 6/15/05.
- NASA, 2005a. *Disaster Management Program Element FY 2005-2009 Plan*. NASA Science Mission Directorate, Earth-Sun System, Applied Sciences Program, Version 1.1, March 16.  
[http://aiwg.gsfc.nasa.gov/esappdocs/progplans/disaster\\_ver1-1.pdf](http://aiwg.gsfc.nasa.gov/esappdocs/progplans/disaster_ver1-1.pdf), accessed 6/15/05.
- NASA, 2005b. *The Crosscutting Solutions Program*. NASA Science Mission Directorate, Earth-Sun System, Applied Sciences Program. <http://science.hq.nasa.gov/earth-sun/applications/cross.html>, accessed 7/27/05.
- NGDC [National Geophysical Data Center], 2005a. *Bathymetry, Topography, & Relief: Surface of the Earth, 2 minute color relief images*. NOAA Satellite and Information Service.  
<http://www.ngdc.noaa.gov/mgg/image/2minrelief.html>, accessed 7/14/05.
- NGDC, 2005b. *2-Minute Gridded Global Relief Data (ETOPO2)*. World Data Center for Marine Geology & Geophysics, Boulder; NOAA Satellite and Information Service.  
<http://www.ngdc.noaa.gov/mgg/fliers/01mgg04.html>, accessed 7/14/05.
- NGDC, 2005c. *NGDC Coastal Relief Model Development*.  
<http://www.ngdc.noaa.gov/mgg/coastal/model.html>, accessed 7/14/05.
- NIBS [National Institute of Building Sciences], 2003. *Research to Develop an Advanced Severe Storm Coastal Risk Assessment Methodology using WAVEWATCH III and NASA's Remote Sensing Technology*. Proposal to NASA.
- NIBS, 2004. *Research to Develop an Advanced Severe Storm Coastal Risk Assessment Methodology in HAZUS-MH using WAVEWATCH III and NASA's Remote Sensing Technology*. Revised draft project work plan under Cooperative Agreement No. NNS04AA05A, July.
- NOAA HRD [National Oceanic and Atmospheric Administration Hurricane Research Division], 2005. *Re-Analysis Project - NOAA Revisits Historic Hurricanes*. Atlantic Oceanographic and Meteorological Laboratory, <http://www.aoml.noaa.gov/hrd/hurdat/>, accessed 7/27/05.
- NOAA CSC [Coastal Services Center], 2005. *Risk and Vulnerability Assessment Tool (RVAT) Glossary*.  
<http://www.csc.noaa.gov/rvat/glossary.html>, accessed 8/5/05.
- Ris, R. C., L. H. Holthuijsen, and N. Booij, 1999. A third-generation wave model for coastal regions, 2. Verification. *Journal of Geophysical Research*, 104(C4): 7667–7682.
- Skerlj, P. F., and P. J. Vickery, 1998. *Risk Consistent Loading Criteria in Regions Influenced by Storm Surge and Hurricane Winds*. Small Business Innovation Research (SBIR) Grant Phase I-9760684, National Science Foundation, Arlington, VA, November.

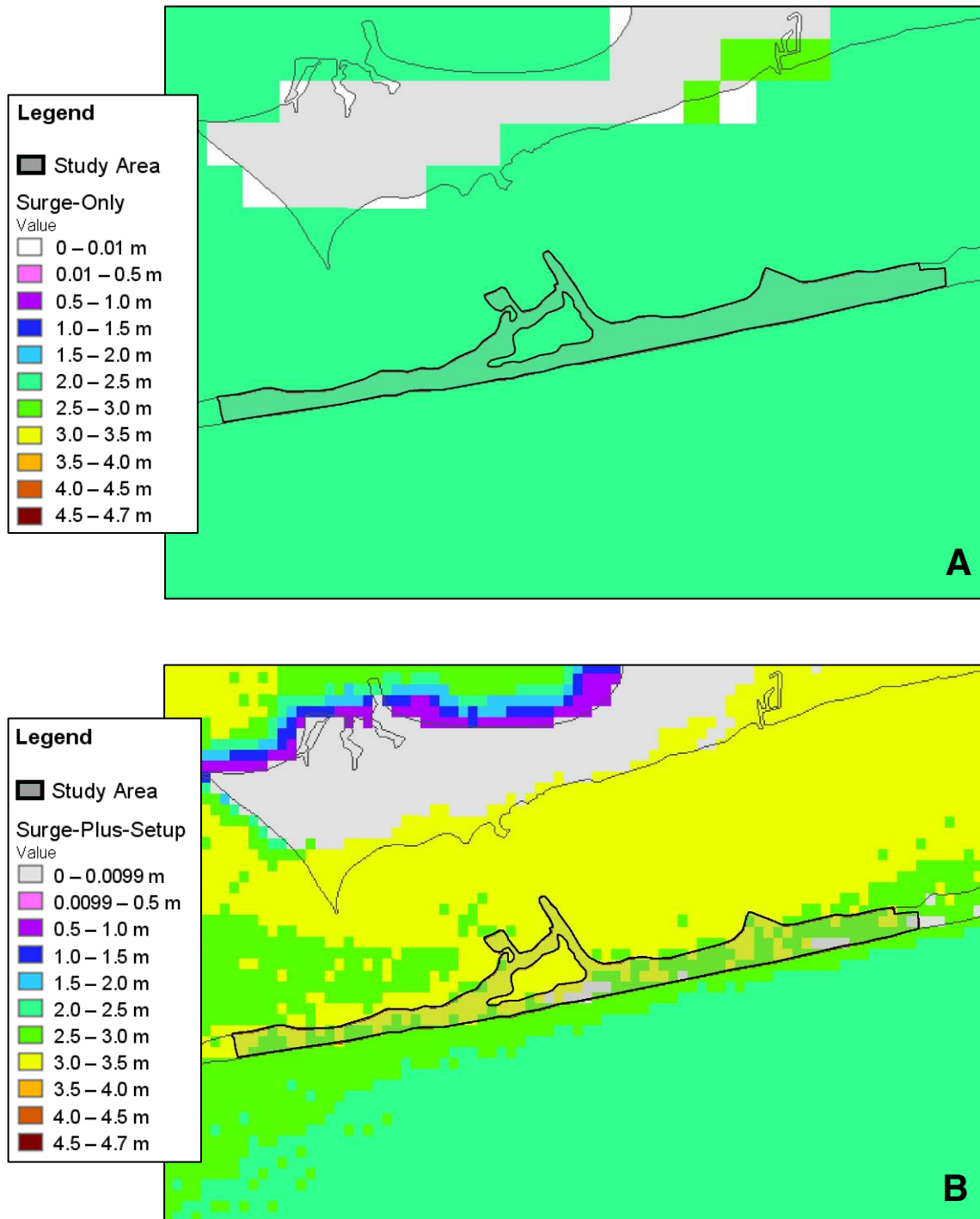
- Skerlj, P. F., P. J. Vickery, and J. X. Lin, 2000. *Modeling of the Combined Action of Hurricane Winds, Surge, and Waves*. Small Business Innovation Research (SBIR) Grant Phase I-9861001, National Science Foundation, Arlington, VA, May.
- State of North Carolina, 2004. Coastal Flood Studies. Revision 5. FEMA Cooperating Technical Partner. [http://www.ncfloodmaps.com/pubdocs/coastal\\_flood\\_studies.pdf](http://www.ncfloodmaps.com/pubdocs/coastal_flood_studies.pdf), accessed 8/5/05.
- Stewart, S. R., 2005. *Tropical Cyclone Report, Hurricane Ivan, 2-24 September, 2004*. Released 12/16/04, revised 6/3/2005. National Weather Service, National Hurricane Center, Tropical Prediction Center, <http://www.nhc.noaa.gov/2004ivan.shtml>, accessed 6/30/05.
- Tolman, H. L., 1999. *User Manual and System Documentation of WAVEWATCH-III Version 1.18*. Technical Note 166, Ocean Modeling Branch, National Centers for Environmental Prediction, National Weather Service, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Washington, DC, 118 p. [http://polar.ncep.noaa.gov/mmab/papers/tn166/OMB\\_166.pdf](http://polar.ncep.noaa.gov/mmab/papers/tn166/OMB_166.pdf), accessed 01/10/06.
- Tolman, H. L., 2002. *User Manual and System Documentation of WAVEWATCH-III Version 2.22*. Technical Note 222, Environmental Modeling Center, Marine Modeling and Analysis Branch, National Centers for Environmental Prediction, National Weather Service, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Washington, DC, 139 p. [http://polar.ncep.noaa.gov/mmab/papers/tn222/MMAB\\_222.pdf](http://polar.ncep.noaa.gov/mmab/papers/tn222/MMAB_222.pdf), accessed 01/10/06.
- Tolman, H. L., J. H. G. M. Alves, and Y. Y. Chao, 2004. *A Review of Operational Forecasting of Wind Generated Waves by Hurricane Isabel at NCEP*. Technical Note 235, Environmental Modeling Center, Marine Modeling and Analysis Branch, National Centers for Environmental Prediction, National Weather Service, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Camp Springs, MD, 51 p. [http://polar.ncep.noaa.gov/mmab/papers/tn235/MMAB\\_235.pdf](http://polar.ncep.noaa.gov/mmab/papers/tn235/MMAB_235.pdf), accessed 01/10/06.
- Twisdale, L. A., and P. J. Vickery, 1992. *Investigation of Predictive Methods for Hurricane Winds in the United States*. Small Business Innovation Research Grant ISI-9160135, National Science Foundation, Washington, DC, July.
- USACE [U.S. Army Corps of Engineers], 1984. *Shore Protection Manual: Volumes 1 and 2*. Coastal Engineering Research Center, Washington, DC.
- U.S. Navy, 2003. *WW3 Model Description*. Fleet Numerical Meteorology and Oceanography Center, [https://www.fnmoc.navy.mil/PUBLIC/WW3/ww3\\_details.html](https://www.fnmoc.navy.mil/PUBLIC/WW3/ww3_details.html), accessed 6/30/05.
- Veri-Tech, Inc., 2005. *SBEACH: Storm-induced BEAch CHange model – Overview*. <http://www.veritechinc.net/products/cedas/sbeach.htm>, accessed 7/14/05.
- Vickery, P. J., P. F. Skerlj, A. C. Steckley, and L. A. Twisdale, 2000a. Hurricane wind field model for use in hurricane simulations. *Journal of Structural Engineering*, 126(10): 1203–1221.
- Vickery, P. J., P. F. Skerlj, and L. A. Twisdale, 2000b. Simulation of hurricane risk in the U.S. using empirical track model. *Journal of Structural Engineering*, 126(10): 1222–1237.

Wang, Z., and P. J. Vickery, 2005 (in press). The integration of a hurricane wind hazard model with deepwater and nearshore wave models. In *Proceedings of Oceans 2005 MTS/IEEE: One Ocean*, Marine Technology Society/IEEE Oceanic Engineering Society, Washington, DC, September 18–23.

WL | Delft Hydraulics, 2005. *SWAN: Simulating Waves Nearshore – Introduction*. <http://www.wldelft.nl/soft/swan/>, accessed 7/14/05.

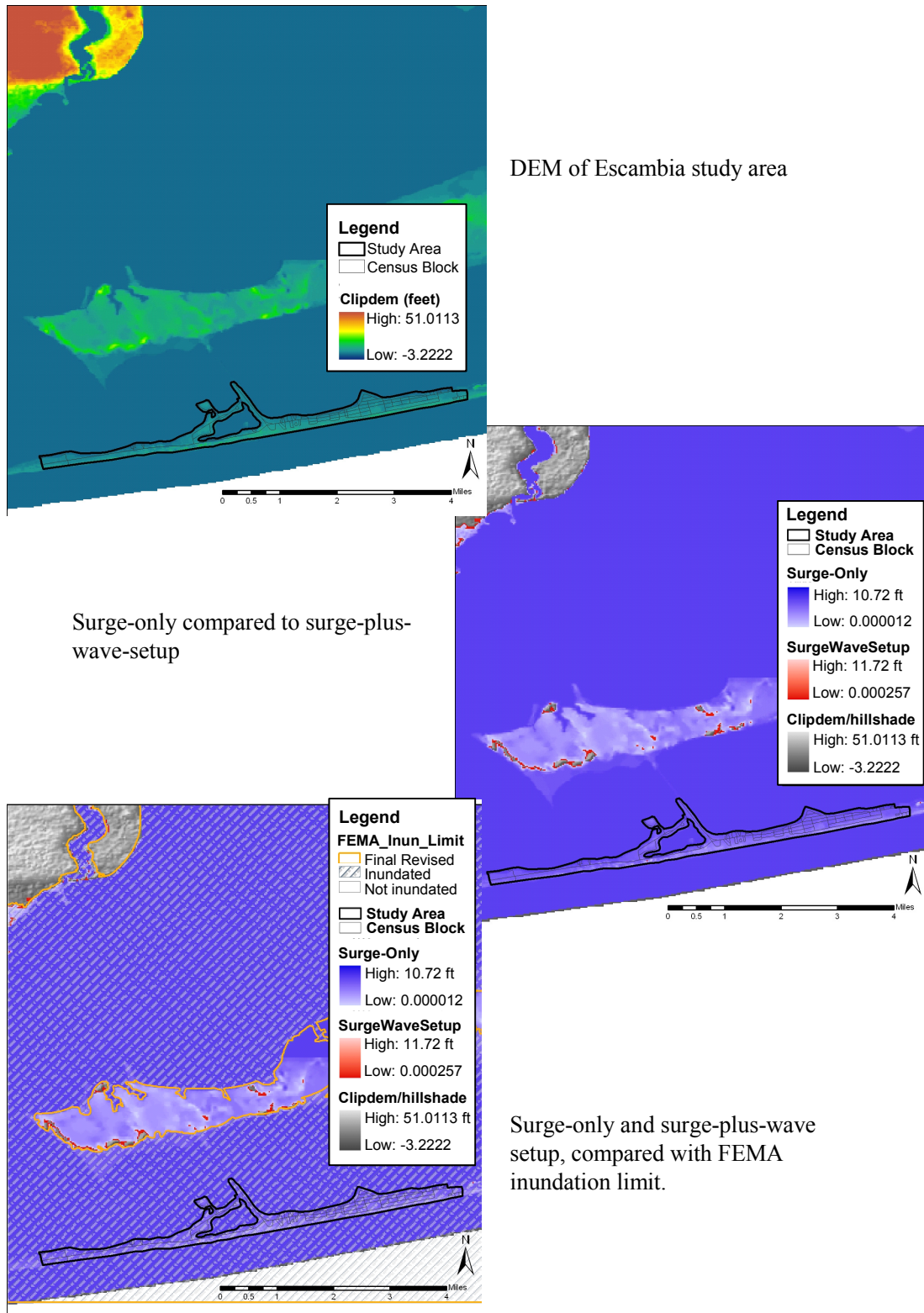


## Appendix A. Additional Figures

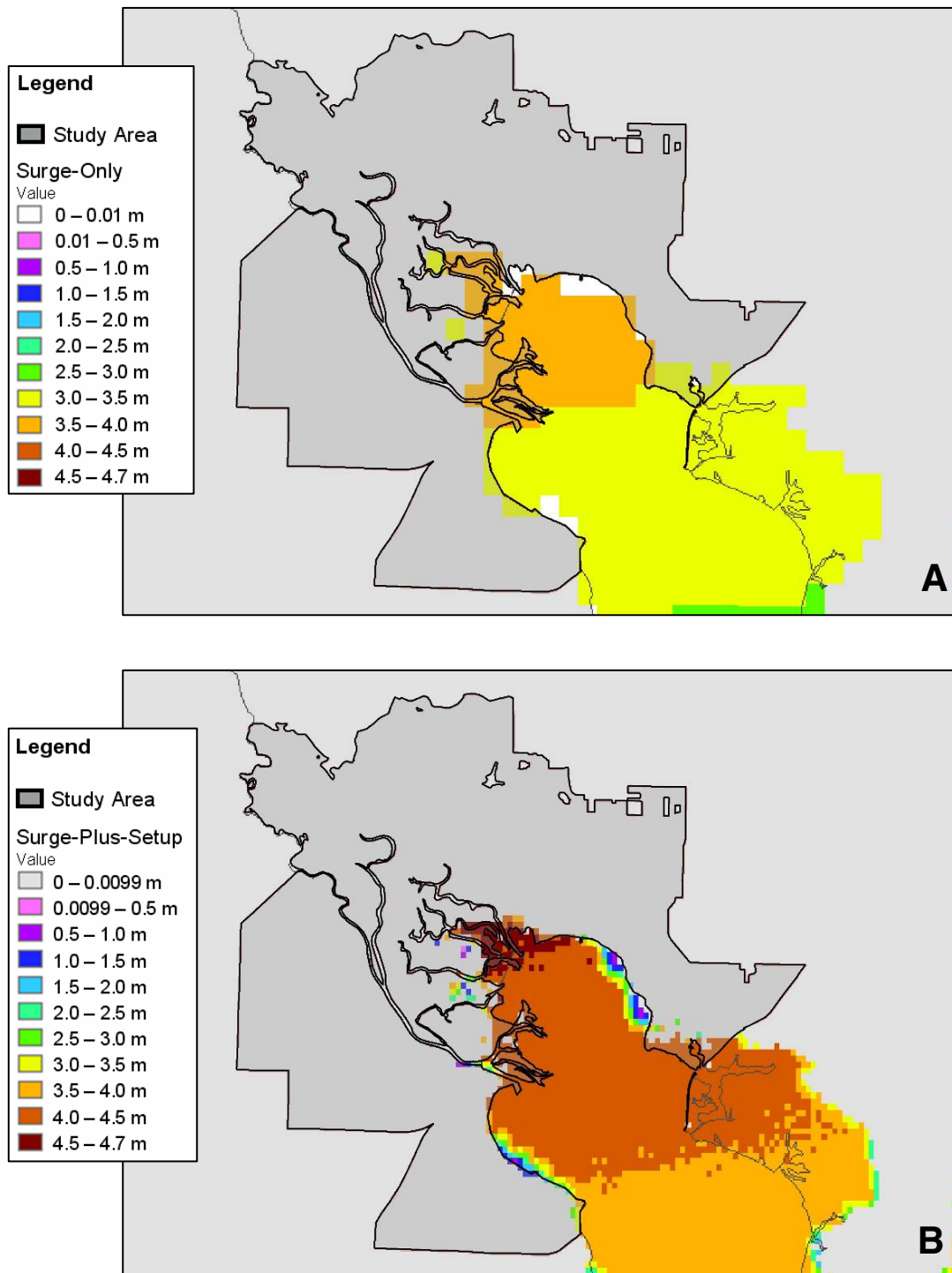


**Figure A-1.** Comparison of surge-only (A) and surge-plus-wave-setup (B) for Escambia study area.

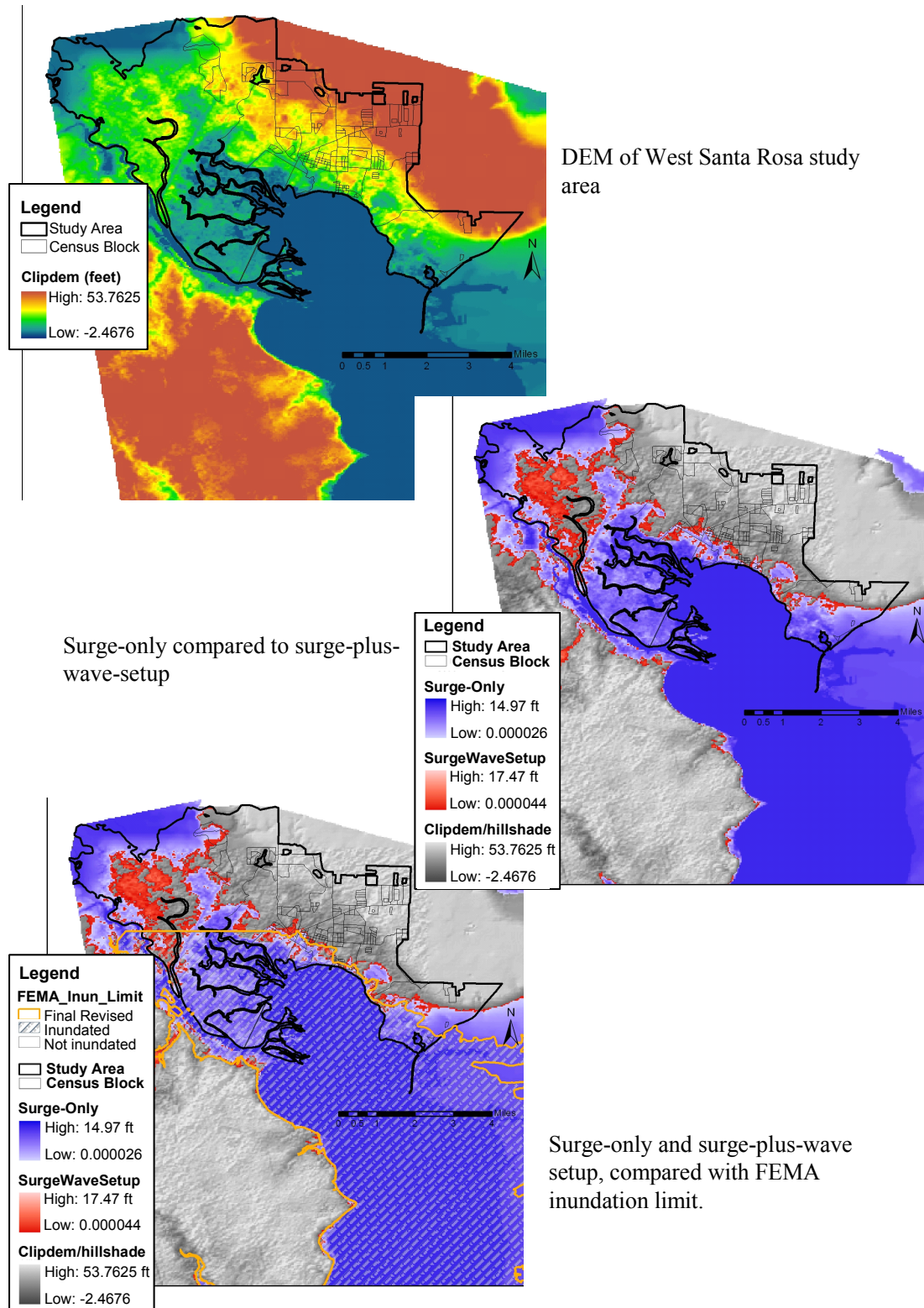




**Figure A-2.** DEM of Escambia study area, resulting inundation extent from inputting water elevation value for surge-only and surge-plus-wave-setup cases into HAZUS-MH MR1 flood module, and comparison of these inundation extents with FEMA inundation limit. Units are in feet.

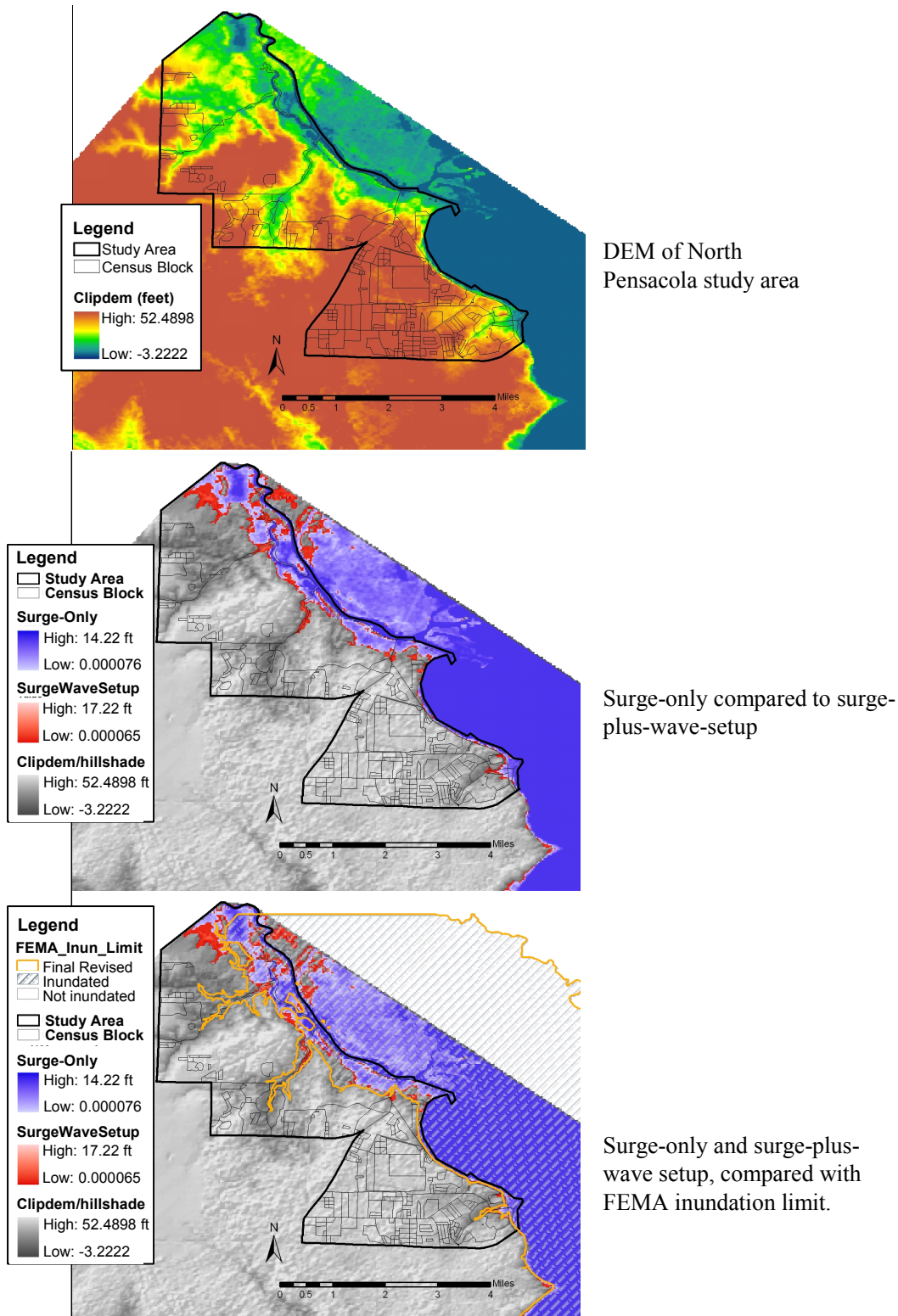


**Figure A-3.** Comparison of surge-only (A) and surge-plus-wave-setup (B) for West Santa Rosa (northeast side) and North Pensacola (southwest side) study areas.

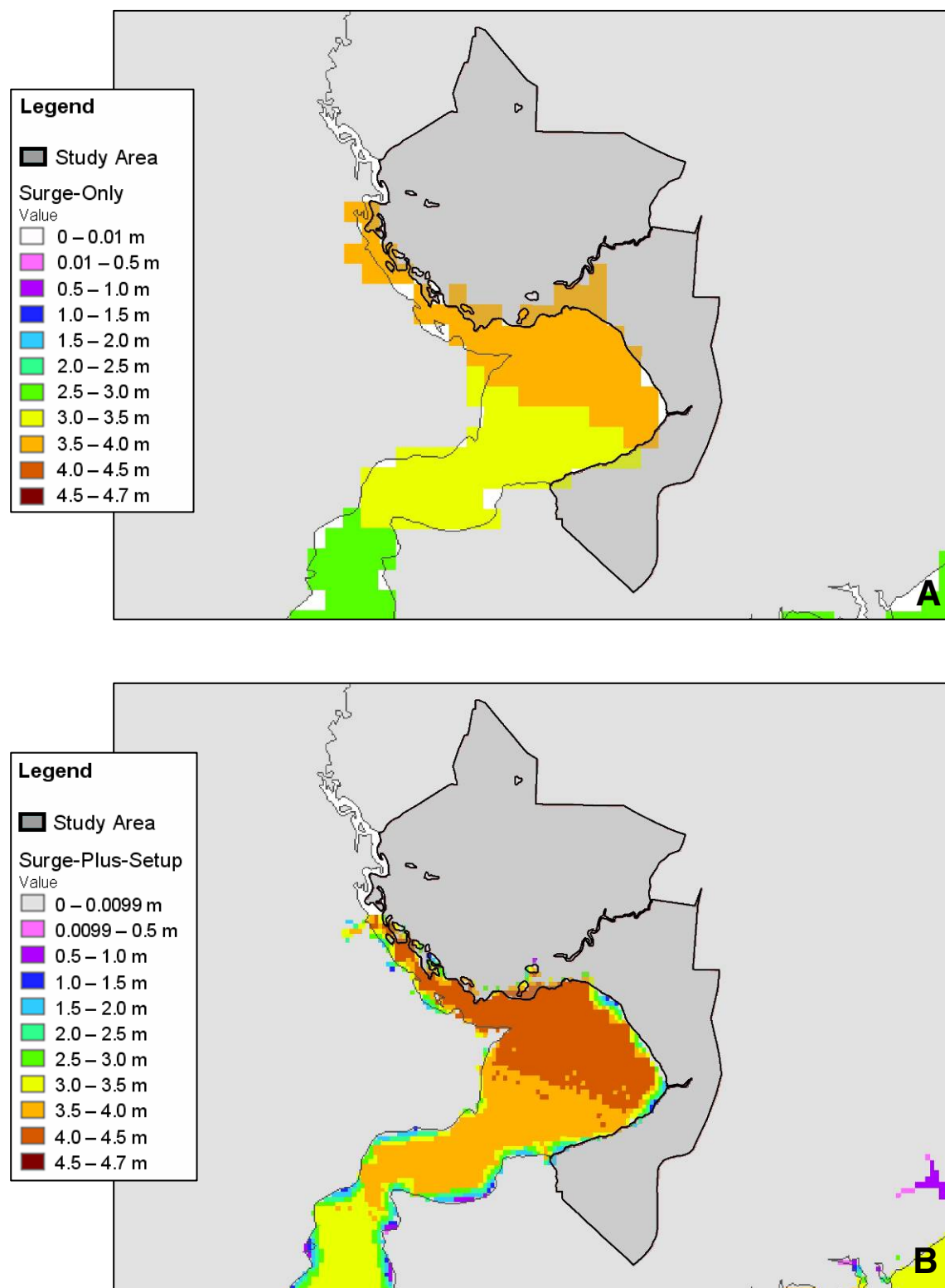


**Figure A-4.** DEM of West Santa Rosa study area, resulting inundation extent from inputting water elevation value for surge-only and surge-plus-wave-setup cases into HAZUS-MH MR1 flood module, and comparison of these inundation extents with FEMA inundation limit. Units are in feet.

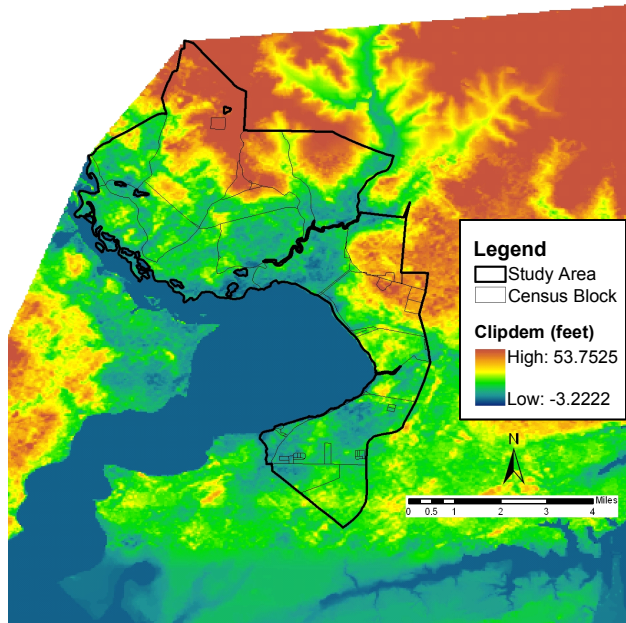




**Figure A-5.** DEM of North Pensacola study area, resulting inundation extent from inputting water elevation value for surge-only and surge-plus-wave-setup cases into HAZUS-MH MR1 flood module, and comparison of these inundation extents with FEMA inundation limit. Units are in feet.

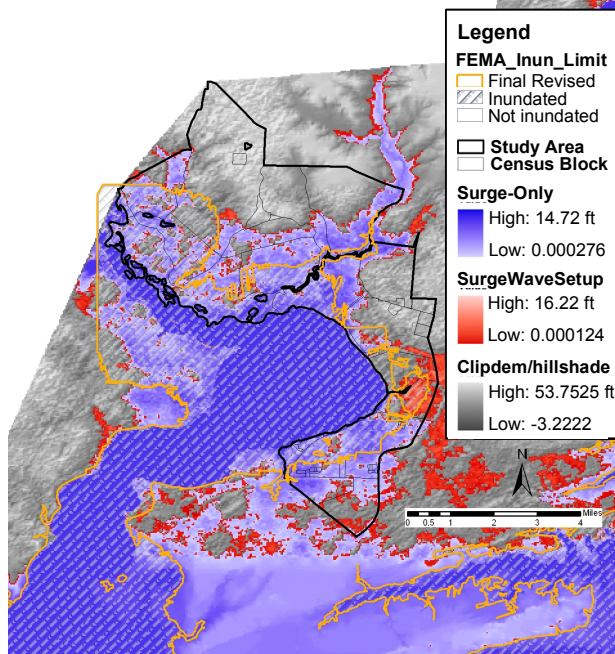
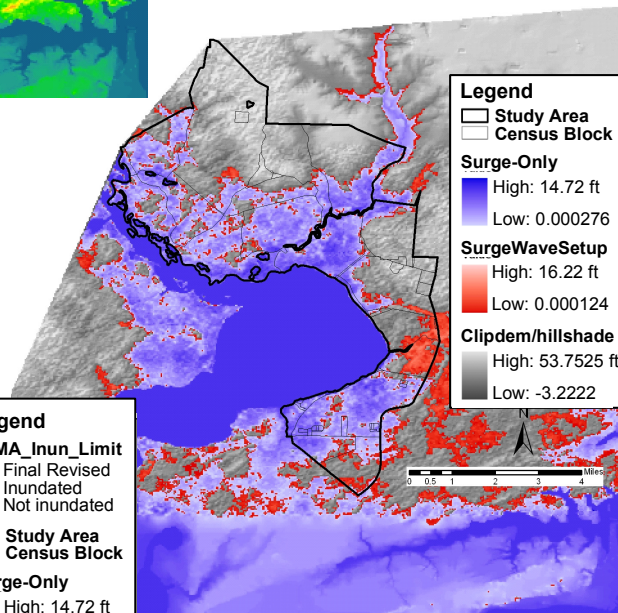


**Figure A-6.** Comparison of surge-only (A) and surge-plus-wave-setup (B) for Perdido Bay study area.



DEM of Perdido Bay study area

Surge-only compared to surge-plus-wave-setup



Surge-only and surge-plus-wave setup, compared with FEMA inundation limit.

**Figure A-7.** DEM of Perdido Bay study area, resulting inundation extent from inputting water elevation value for surge-only and surge-plus-wave-setup cases into HAZUS-MH MR1 flood module, and comparison of these inundation extents with FEMA inundation limit. Units are in feet.

*This page intentionally blank*

## Appendix B. Results from HAZUS-MH flood module for all study areas and case runs

**Table B-1.** Selected results from the “Flood Event Summary Report” produced by HAZUS-MH MR1 flood module for all study areas and case runs.

Study Area	Baldwin Beaches		Escambia		West Santa Rosa		North Pensacola		Perdido Bay	
Study Case Scenario	Surge-Only	Surge-Plus-Wave-Setup	Surge-Only	Surge-Plus-Wave-Setup	Surge-Only	Surge-Plus-Wave-Setup	Surge-Only	Surge-Plus-Wave-Setup	Surge-Only	Surge-Plus-Wave-Setup
Size of study region (in square miles)	79		2		29		17		27	
Number of census blocks	544		78		185		238		65	
Number of households	>6000		>1000		~3500		>10000		>2000	
Total population (2000 Census Bureau data)	<12900		<2500		11000		>24000		>6000	
Total number of buildings in region	~7650		~1465		~4000		~8450		~2440	
Total building replacement value (excluding contents) (2002 dollars; in millions)	\$1341		\$305		\$478		\$1438		\$324	
Percentage of buildings associated with residential housing	98		99		99		99		99	
Percentage of building value associated with residential housing	85		93		86		83		90	
Stillwater elevation used in HAZUS-MH flood module (in feet)	9	10	7.5	8.5	12.5	15	11	14	11.5	13
Tons of debris generated	171494	206112	33942	54570	7671	16182	6598	13271	19410	29104
Percentage of finishes (dry wall, insulation, etc.)	44	42	49	41	27	25	32	26	39	35
Percentage of structural debris (wood, brick, etc.)	31	33	31	36	38	38	41	39	34	36
Percentage of foundations (concrete slab or block, rebar, etc.)	25	25	20	23	35	37	27	35	27	29
Number of truckloads (at 25 tons/truck) needed to remove debris	6860	8244	1358	2183	307	647	264	531	776	1164
Number of households displaced due to flood (includes evacuees)	3173	3306	820	830	83	160	134	66	445	449
Number of folks seeking temporary shelter in public shelters	8513	8893	2038	2062	165	284	371	170	1252	1244
Total economic loss estimated for flood (in millions)	\$546.1	\$635.76	\$142.37	\$189.12	\$16.35	\$29.36	\$33.68	\$55.72	\$78.33	\$108.15



Benchmarking the Integration of WAVEWATCH III Results into HAZUS-MH®: Preliminary Results

Study Area	Baldwin Beaches		Escambia		West Santa Rosa		North Pensacola		Perdido Bay	
Study Case Scenario	Surge-Only	Surge-Plus-Wave-Setup	Surge-Only	Surge-Plus-Wave-Setup	Surge-Only	Surge-Plus-Wave-Setup	Surge-Only	Surge-Plus-Wave-Setup	Surge-Only	Surge-Plus-Wave-Setup
Percentage of total replacement value of region's buildings	41	47	47	62	3	6	2	4	24	33
Total building-related losses (direct building losses and business interruption losses) (in millions)	\$546.1	\$635.76	\$142.37	\$189.12	\$16.35	\$29.36	\$33.68	\$55.72	\$78.33	\$108.15
Percentage of estimated losses related to business interruption	38	35	40	42	28	24	21	20	50	48
Percentage of total loss that were residential occupancies	58.51	59.99	61.7	62	56.5	62.63	37	35.62	43.62	45.43
Building loss (building, content, inventory) (in millions)	\$339.96	\$410.88	\$85.63	\$109.62	\$11.7	\$22.25	\$26.73	\$44.64	\$39.1	\$56.38
Business interruption (income, relocation, rental income, wage) (in millions)	\$206.15	\$224.88	\$56.74	\$79.5	\$4.65	\$7.12	\$6.95	\$11.08	\$39.24	\$51.78
Difference in total economic loss estimated for flood (in millions)	\$89.66		\$46.75		\$13.01		\$22.04		\$29.82	
Percent difference in total economic loss estimated for flood	15.17		28.21		56.92		49.31		31.98	

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
<p>The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</p> <p><b>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</b></p>					
1. REPORT DATE (DD-MM-YYYY) 30-12-2005		2. REPORT TYPE Benchmarking Report: Preliminary		3. DATES COVERED (From - To) Apr 2005 - Dec 2005	
4. TITLE AND SUBTITLE Benchmarking the Integration of WAVEWATCH III Results into HAZUS-MH®: Preliminary Results				5a. CONTRACT NUMBER NASA Task Order NNS04AB54T	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Judith Berglund, Donald Holland (1) Rodney McKellip (2) Jeff Sciaudone, Peter Vickery, Zhanxian Wang, Ken Ying (3)				5d. PROJECT NUMBER SWR C05C-SE15-13	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) (1) Science Systems and Applications, Inc., Bldg. 1105, John C. Stennis Space Center, MS 39529 (2) Applied Sciences Directorate, National Aeronautics and Space Administration, Bldg. 1100, John C. Stennis Space Center, MS 39529 (3) Applied Research Associates, Raleigh, NC				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Applied Sciences Directorate, National Aeronautics and Space Administration, Code MA00, Bldg. 1100, John C. Stennis Space Center, MS 39529				10. SPONSORING/MONITOR'S ACRONYM(S) NASA ASD	
				11. SPONSORING/MONITORING REPORT NUMBER SSTI-2220-0080	
12. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified/Publicly available STI per NASA Form 1676					
13. SUPPLEMENTARY NOTES to be posted on the NASA GSFC Applications Implementation Working Group Web site at <a href="http://aiwg.gsfc.nasa.gov/">http://aiwg.gsfc.nasa.gov/</a>					
14. ABSTRACT The report summarizes the results from the preliminary benchmarking activities associated with the use of WAVEWATCH III (WW3) results in the HAZUS-MH MR1 flood module. Project partner Applied Research Associates (ARA) is integrating the WW3 model into HAZUS. The current version of HAZUS-MH predicts loss estimates from hurricane-related coastal flooding by using values of surge only. Using WW3, wave setup can be included with surge. Loss estimates resulting from the use of surge-only and surge-plus-wave-setup were compared. This benchmarking study is preliminary because the HAZUS-MH MR1 flood module was under development at the time of the study. In addition, WW3 is not scheduled to be fully integrated with HAZUS-MH and available for public release until 2008.					
15. SUBJECT TERMS WAVEWATCH III, HAZUS-MH, storm surge, wave setup, loss estimates, Disaster Management					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19b. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Rodney McKellip
U	U	U	UU	42	19b. TELEPHONE NUMBER (Include area code) (228) 688-2984